SCOTTISH NATURAL HERITAGE

RSM No 144

Coastal Cells in Scotland: Cell 2 – Fife Ness to Cairnbulg Point

D L Ramsay & A H Brampton

2000

SCOTTISH NATURAL HERITAGE

Research, Survey and Monitoring

REPORT

Coastal Cells Research co-funded by: The Scottish Office Agriculture, Environment and Fisheries Department, Historic Scotland and Scottish Natural Heritage.

THE SCOTTISH OFFICE HISTORIC SCOTLAND SCOTTISH NATURAL HERITAGE

RSM No 144

Coastal Cells in Scotland:
Cell 2 – Fife Ness to Cairnbulg Point

D L Ramsay & A H Brampton

2000

D L Ramsay & A H Brampton, HR Wallingford Ltd, Howbery Park,
Wallingford, Oxon OX10 8BA

Nominated Officer:	George Lees, Advisory Services
Report date:	1998
Report to:	Scottish Natural Heritage
Contract No:	RASD/139/96/ESB

This report should be cited as follows:

Ramsay, D.L. & Brampton, A.H. 2000. Coastal Cells in Scotland: Cell 2 – Fife Ness to Cairnbulg Point. Scottish Natural Heritage Research, Survey and Monitoring Report No 144.

Scottish Natural Heritage
Publications Section
Battleby, Redgorton, Perth PH1 3EW
UNITED KINGDOM

Scottish Natural Heritage
Advisory Services
2 Anderson Place, Edinburgh EH6 5NP
UNITED KINGDOM

ISSN 1350-3111

CONTENTS

Note: *Due to their size, the maps in Appendix 2 have not been reproduced within this report, but are available for inspection, by prior arrangement, at the* Earth Science Group, Advisory Services, Scottish Natural Heritage, 2 Anderson Place, Edinburgh EH6 5NP.

Summary

This report reviews the coastline between Fife Ness and Cairnbulg Point on the east coast of Scotland. It describes the various coastal characteristics and processes which affect the regime of this particular stretch of shoreline. The report includes a description of the major coastal features, processes, and defences along with other aspects of beach development. The stretches of coastline which, for coastal management purposes, can be treated as independent or semi-dependent cells are also identified.

The study was carried out for Scottish Natural Heritage, The Scottish Office Agriculture, Environment and Fisheries Department and Historic Scotland by the Coastal Group at HR Wallingford. The contract was administered by Dr George Lees of Scottish Natural Heritage. For further details of the study please contact Mr Douglas Ramsay or Dr Alan Brampton of the Coastal Group at HR Wallingford.

Note

This contract was undertaken prior to the establishment of The Scottish Executive. The report therefore contains references to The Scottish Office and The Secretary of State for Scotland. The following changes therefore apply and should be borne in mind when reading the report.

Previous terminology	*Present*
The Secretary of State for Scotland	The First Minister
The Scottish Office Agriculture, Environment and Fisheries Department	The Scottish Executive Rural Affairs Department

1 *Introduction*

1.1 General

In January 1996, HR Wallingford was commissioned by Scottish Natural Heritage, (SNH), the Scottish Office Agriculture, Environment and Fisheries Department, (SOAEFD) and Historic Scotland, (HS) to extend an existing study, (HR Wallingford, 1997) to define Coastal Cells and Sub-cells around the coastline of Scotland. This report, which reviews the coastline of Cell 2 between Fife Ness and Cairnbulg Point, is one of a series of 11 reports covering the entire coastline of mainland Scotland, the Western Isles, Orkney and Shetland. The study concentrates on identifying and describing the various natural and man-made characteristics and processes which affect the behaviour of this particular stretch of coastline. The report includes a description of the dominant hydraulic processes, areas of erosion and accretion, coastal defences and various other aspects of the coastal regime. The aim of the report is to provide an overall understanding of the character and processes occurring within each sub-cell to allow as full an appreciation as possible of the coastal regime on a macro scale.

1.2 Terms of reference

The terms of reference for this study were detailed by Scottish Natural Heritage in Annex A of their Project Specification. The aims are to provide:

(i) a basic description of coastal cells and their significance,

(ii) maps of each cell showing the location and boundaries of all sub-cells contained therein and the nature of the cell boundaries,

(iii) a map of each sub-cell showing the general direction(s) of littoral drift therein and known areas of erosion and accretion,

(iv) a map of each sub-cell showing the location of all sites designated for their nature conservation interest,

(v) a map of each sub-cell showing the location of sites designated for their historical or archaeological interest,

(vi) a map of each sub-cell showing the location of all principal coastal protection works and beach monitoring schemes,

(vii) descriptions for each sub-cell of the following characteristics and processes:

- geology and geomorphology
- wave and tidal regime
- areas of erosion and accretion and, where information exists, details of any rates of change
- assessment of existing erosion problems
- a summary of the relevance or implications of the littoral processes identified to sites of nature conservation interest
- a summary of the susceptibility of historical and archaeological sites to coastal erosion

- existing coastal protection and management measures (including dredging and spoil disposal)
- present monitoring arrangements
- assessment of sensitivities of sites to climatic change and sea level rise.

1.3 Outline of report

A general introduction to the concept of coastal cells, and how the concept has been applied to the coastline of Scotland is provided in Chapter 2. Chapter 3 provides some general background information on the marine environment in the context of coastal cells. Chapter 4 provides reference to data sources of relevance to coastal management in Cell 2. Chapter 5 forms the main body of the report. A brief description of Cell 2 detailing all the cell and sub-cell boundaries is given. For each sub-cell, a description of its character and the processes occurring there is detailed. An assessment of climatic change, sea level rise, and the likely effects on the coastline of Cell 2 is given in Chapter 6, with Chapter 7 listing the references used. A listing of Sites of Special Scientific Interest, the locations of noted historical and archaeological sites, useful addresses and a glossary of terms used is contained within the appendices of this report.

2 *Coastal Cells within Coastal Planning and Development*

2.1 Coastal Cells

The concept of Coastal Cells was introduced in an initial document identifying the main cells around the coastline of Scotland, (HR Wallingford, 1997), and in a similar document for the coastline of England and Wales, (HR Wallingford, 1993a). The description below summarises the significance and importance of such cells in managing the coastline with regard to the naturally occurring processes acting upon it.

The processes which shape and alter a coastline show no respect for administrative boundaries. Coastal defences installed by one local authority have, at some sites in the UK, contributed to erosion along frontages under the care of an adjacent authority. These difficulties can be avoided by recognising the natural divisions of a coastline, often called coastal "cells". Where the main concern in managing a shoreline is to defend against erosion or flooding, then the most useful definition of a cell is based on a consideration of the longshore drift of beach material (sand and shingle). This is because most cases of severe coastal erosion are caused by interruptions to the natural longshore transport of sediment.

A recent study of the coastline of England and Wales, (HR Wallingford, 1993a), resulted in its suggested division into 11 main cells, each of which was further divided into sub-cells. An ideal cell would be entirely self-contained from a sediment transport viewpoint, i.e. there would be no nett import or export of beach material. Then, although coastal defence works could affect the whole cell by interrupting the longshore drift, they cannot affect beaches in other cells. Once established, these cells (and sub-cells) have proved to be a useful basis for shoreline management purposes. In England, the Ministry of Agriculture, Fisheries and Food (MAFF) have introduced Shoreline Management Plans; these are drawn up to provide a strategic basis for planning future coastal defences. Apart from considering aspects such as waves, tidal levels and coastal erosion/accretion, these Plans consider wider issues. Typically these include land use, ecological and geological conservation, tourism and recreation etc. As a consequence, in England and Wales, these plans provide a useful input into wider Coastal Zone Management initiatives. Each Plan is normally carried out for one or more sub-cells as defined above. An initial study has just been completed into defining coastal cells around the coastline of mainland Scotland, Orkney, Shetland and the Western Isles, (HR Wallingford, 1997).

On rocky coastlines, where sediment is sparse, and beaches are often confined to deeply indented bays, then "cells" are often small and numerous. It becomes impractical in such areas to draw up a management plan for each cell; as a result it is sensible to group a number of these small bays together, to form a more convenient "cell" in this report. Considerations other than just the longshore transport of beach material are used to define cells in these situations. These include general orientation of the coastline and its hydraulic environment.

Bearing the above description of cell boundaries in mind, the coast of Scotland has been divided up into 11 main "cells" as shown in Figure 1. These major cells not only reflect beach sediment units, but also divide the coast into regions where the geology, physical character and orientation are similar.

For the purposes of coastal defence management, however, these major cells may be rather large, and contain too many conservation organisations, local authorities etc. for a single group to manage. Within these major cells, therefore, a number of "sub-cells" have been defined, and the description of the coast in this report is arranged using these smaller units. At many sites, the sediment transport around a headland or a large harbour only moves in one direction, and is often of small volume. Engineering works on the updrift side of such a feature may therefore have some impact on the downdrift coast, but such impacts may be small or totally insignificant. Interference with the beaches downdrift of such a "one-way" valve will not affect beaches updrift. We can regard such sub-cells as being "partly dependent", with the understanding that the cell boundary between them is not totally "sediment-tight". An idealised cell is shown in Figure 2.

The definitions of cells and sub-cells in this report are principally derived from the viewpoint of movement of sand and shingle along the beaches, and taking into account the likely consequences of interfering with that movement, i.e. sediment movement in the littoral zone, Figure 3. A particular difficulty arises, however, in estuaries, which are often 'sediment sinks' and hence suitable cell boundaries. For those interested in the biological aspects of an estuary, or the movements of cohesive sediments, this separation of the estuary into two cells is inconvenient. To avoid this, we have preferred to define cell, (and sub-cell) boundaries, around Scotland on the basis of 'drift divide' points (e.g. headlands). The inner portions of several major firths have then been defined as sub-cells.

Identification of such coastal cells is intended to help planners determine the length of coastline likely to be affected by coastal works in a particular area. It is hoped that this type of 'overview' will assist in the understanding of the coastal system as a whole and may lead to a more unified approach to the planning of coastal defences, and hence assist in wider Coastal Zone Management.

2.2 Coastal planning and development

In England and Wales, Shoreline Management Plans co-ordinated with other initiatives can provide useful information in informing decisions on statutory policies, for example in areas which face particular pressures such as in estuaries where competing usage is often experienced. An example, from England and Wales, of the inter-relationship between some of these initiatives is shown in Figure 4. Local authorities are required to produce a structure and local plan which together provide the Development Plan for an area. The Development Plan provides the statutory framework within which development control decisions are made. Shoreline Management Plans should be integrated within the work of the local authority and can have an important role in informing development plan policy.

There are several documents available which highlight the Government policy on key issues affecting the coastal zone. Of most relevance to the coastline of Scotland is the recently published discussion document from the Scottish Office on *Scotland's Coast* (Scottish Office, 1996) and *National Planning Policy Guidelines (NPPG)13: Coastal Planning* (Scottish Office, 1997). Similar publications in England and Wales, despite being geared to the legislative framework in these countries, are also of use in highlighting the key issues affecting the Scottish coastline. Of particular note, in the context of this report, is the Department of Environment (DoE) publication on *Policy guidelines for the coast* (DoE, 1995) and the MAFF publication, *Shoreline Management Plans - A guide for coastal authorities* (MAFF, 1995a).

2.3 Coast protection legislation in Scotland

The new Unitary Authorities with a coastal frontage are known as coast protection authorities under the Coast Protection Act 1949 and have powers under the Act to undertake such coast protection works as they consider necessary to protect any land in their area. Where coast protection work proposed is not maintenance and repair, the coast protection authority is required to follow the procedures defined in the Act. This may lead to approval by the Secretary of State. Once a scheme is approved by the Secretary of State, government grants are available towards the eligible cost of the works at a rate dependant on the authority promoting the scheme. The grant level can vary from between 20%-80% at present.

The seabed below the Mean Low Water Mark of Ordinary Spring Tides is owned by the Crown Estate *prima facie* in law. The Crown Estate also owns much of the foreshore between Mean High and Mean Low Water Springs but does not hold a title to the foreshore and ownership can be displaced by anyone who can show a title derived from a Crown Grant. As part of the process required to enable consideration of schemes for approval under the Coast Protection Act 1949, consultation with the Crown Estate Commissioners is required. Approval must be obtained from the Commissioners before any coastal defence works, or any works on Crown Estate property is carried out.

Planning permission will be required for all new coastal defence works above Mean Low Water Mark of Ordinary Spring Tides and for any associated works such as borrow pits. In addition, building warrants are normally required for the construction of all walls and structures over a certain height. The exceptions to this are where work is being conducted within harbour limits and are covered by the Harbour Act 1964; for maintenance work; and for emergency works. There are a number of other consents which may be required before coastal defence work can be undertaken. Some of these are detailed in the table below:

Table 1 Required consents for proposed coast protection works

Consent	Application
Planning Permission (TCPSA 1997)	. All new works above MLWS . Associated works such as borrow pits above MLWS
Coast Protection Authority (CPAu) consent (CPA 1949)	. All coast protection works other than those carried out by a CPAu in its own area . New works carried out by a CPAu in its own area require consent of SoS (Scotland)
FEPA Licence (FEPA 1985, part II)	. Licence required for all operations entailing construction or deposition on seabed below MHWS
Environmental Statement (ES) (EA 1988/1994)	. If Planning Authority considers significant environmental effects to a "sensitive location" [1] will result from proposed works, it can require an ES with planning application
Notice of Intent (WCA 1981 Sn28)	. If works are permitted development on an SSSI

Notes

[1] Indicative criteria for assessing the significance of such impacts are contained within the Environmental Assessment legislation referred to.

Abbreviations used:

- CPA 1949: Coast Protection Act 1949
- CPAu: Coast Protection Authority
- EA 1988/1994: Environmental Assessment (Scotland) Regulations as amended
- ES: Environmental Statement
- FEPA 1985: Food and Environment Protection Act 1985
- SoS: Secretary of State
- TCPSA 1997: Town and Countryside Planning (Scotland) Act 1997
- WCA: Wildlife and Countryside Act 1981

Details of the statutory designations, and consultees, of conservation, historical and archaeological sites are described in Section 3.6.

3 The marine environment

3.1 Introduction

This chapter provides a brief general introduction to the coastal environment of Scotland in the context of this report. For more detailed information the reader is referred to the recently published CIRIA manuals *The use of rock in coastal engineering* (CIRIA, 1991) and the *Beach management manual* (CIRIA, 1996).

3.2 Geology and geomorphology

Scotland is composed of a particularly wide range of different rock types, representing most periods of geological time. Sedimentary rocks (those formed by the consolidation and lithification of sediments deposited in different marine and non-marine environments), igneous rocks (those formed by the solidification of lava erupted on the surface of the land or of magma which consolidated within the Earth's crust) and metamorphic rocks (those formed by the alteration or deformation of other rock types) are all well-represented around the coastline.

In geological terms, Scotland can be considered as being formed of five distinct units or divisions, each separated by a major fault or fracture in the Earth's crust:

- the north-west Highlands and Islands west of the Moine Thrust, composed of "ancient" Lewisian gneiss;
- the Northern Highlands between the Moine Thrust and the Great Glen Fault, composed of the eroded roots of the Caledonian Mountain Belt, consisting primarily of 1,000 Ma year old metamorphosed sediments of the Moine;
- the Central Highlands between the Great Glen Fault and the Highland Boundary Fault, composed of 800 Ma year old Dalradian sediments and intruded with granites now forming the Cairngorms and other mountains and hills;
- the Midland Valley, composed of sediments deposited in tropical seas three-hundred million years ago, extensive lava fields of the Ochils and Clyde plateau and the volcanic rocks of Edinburgh and the Laws of Fife and East Lothian; and
- the Southern Uplands, composed of sediments deposited in the former Iapetus Ocean which, for over 100 Ma separated Scotland and England.

The geological structure and the lithological variability exert a strong influence on the morphology of the coastline. However, it is the processes which have occurred over the last ca. 2,000,000 years (during the period known as the Quaternary) that have left a major impact on the coastline, in particular those during the last (Late Devensian) glaciation (ca. 26,000-10,000yrs) and in the postglacial period or Holocene.

The last ice sheet, which reached a thickness of 1500 metres in places, advanced from the Highlands over the entire Scottish mainland and most of the islands. Ice extended off-shore and local ice-caps may have existed on the more remote island groups such as Shetland and the Western Isles. Sea level, world-wide, was up to 140 metres lower than it is today. This, and earlier ice sheets, extensively scoured and eroded the bedrock, particularly in the west where it carved out the fjords and sea lochs along lines of pre-existing geological weakness. By 13,000 years ago the ice sheet had melted, depositing a variable cover of drift off-shore in the process. On-shore the ice deposited a thick cover of till in the more eastern areas. Meltwater from the retreating ice also deposited glaciofluvial deposits in the major eastern valleys and coastal lowlands. As sea level rose during deglaciation, some of the glacial sediments in the off-shore zone were reworked and moved into the present coastal zone, and fresh material was eroded from the glacial deposits on the coast. It is the material derived from these glacial deposits which supplied the majority of the sediment for the sand and shingle beaches of the present coastline.

As the ice sheet melted, the loading it applied on the Earth's crust was removed, resulting in the land recovering, or rising, typically at rates of a few millimetres per year (known as isostatic uplift). Rates varied, however, being greater where the ice was formerly thickest and less where the ice had been thinner, as was the case, for instance, around the Northern and Western Isles. At the same time, melting of the ice sheets caused global sea level to rise (known as eustatic rise). Accordingly, the patterns of relative sea level change during and since the ice age have varied around the country depending upon each location's proximity to the centre of the former ice sheet.

When the ice first began to melt, between approximately 17,000 and 15,000 years ago, global or eustatic sea level rose, flooding over the continental shelf and engulfing many coastal areas. In some western areas, such as Jura and Arran, "raised" beaches were deposited on the coast at heights of up to 40m above present day high water mark. Thereafter, isostatic uplift gradually overtook eustatic rise causing a relative fall in sea levels around most of the country. This trend continued, with local variations, until around 8,000-9,000 years ago, bringing sea level down to around or below present day levels in most areas. At that time, eustatic rise once more overtook isostatic uplift and relative sea level rose again (known as the Post-glacial Transgression) to attain a maximum height relative to the land, in most areas, around 5,00-6,000 years ago.

Since that time eustatic rise has tailed off and so isostatic uplift has caused, in general, a gradual fall in relative sea level of around 1-2 millimetres per year in Scotland, though recent studies suggest that changes in sea level related to global climate change may now be counteracting this. Moreover, in areas remote from the centre of the main Scottish ice cap, such as the Northern and Western Isles, eustatic rise in sea level has continued to outpace isostatic uplift and so gradual submergence has dominated in these areas in recent millennia, rather than emergence.

3.3 Hydraulic processes

In understanding the recent (and past) evolution of the coastline a knowledge of the prevailing tidal levels, currents, wave and swell conditions is necessary.

<u>Tidal levels</u>

Tidal levels experienced around the Scottish coastline are generally made up of two components, an astronomical component and residual component due to weather effects. The main tidal driving forces are the "astronomical forces'"- the major contribution being due to the relative motions of the Earth, Moon and Sun. The differential gravitational effects over the surface of the oceans cause tides with well defined "semi-diurnal" and "diurnal" periods (actually about 12.38 and 24.76 hours respectively).

In addition to the contribution to the tides which results from the earth's rotation, other periods are apparent in the fluctuation of tidal levels, for example the fortnightly spring-neap cycle, corresponding to the half period of the lunar cycle. Due to the slight ellipticity of the earth's orbit around the sun, there is also an annual variation of tidal effects. The solar tidal components are also increased due to declinational effects giving rise to the equinoctal tides in September and March. Even longer variations can also be identified, such as that of approximately 18.6 years which corresponds to the changing angle between the axis of the earth and the plane of the moon's orbit.

Analysis of tidal measurements takes advantage of the knowledge of these precisely known periods, and uses a "harmonic" analysis of the measured data to derive information on the phase and magnitude of each tidal constituent, i.e. a component with a defined period. By analysis of the range (i.e. the vertical difference between high and low water levels), and the timing of the arrival of high/low waters, considerable light can be shed on the propagation of tides around the coast. All the tidal energy experienced around the coastline of Scotland stems from the Atlantic and were it not for the openings to the Atlantic, there would be no noticeable tide in the North Sea. Once the tidal energy reaches the shallow waters of the north-west European continental shelf, however, it becomes concentrated by both the reducing water depth and the converging land-masses. A large number of complex processes then occur, including reflections and complicated swirling motions around areas of little or no tidal range (so called *amphidromic points).*

Sufficient information to predict tides with reasonable accuracy can be gathered in as little as four weeks (a Spring-Neap tidal cycle) in most locations. However, longer periods of recording are necessary to accurately determine all the components. Some of the most influential components, or "harmonics", are normally presented in Tide Tables. It is possible to purchase software (a) to analyse tidal measurements, and/or (b) to use the resulting (or published) harmonics to make your own predictions of water levels. Yearly predictions of water levels are published in the Admiralty Tide Tables. The tide tables also tend to give levels relative to "Chart Datum" and the relationship between the particular "Chart Datum" and a more "universal" vertical datum, e.g. Ordnance Datum Newlyn (ODN) in the UK, must always be carefully established. **For the design of coastal works, it is better to use information derived from analysis of recorded water levels (see below), related to a land-based vertical datum, e.g. ODN.**

Actual water levels experienced around the coastline will vary from those predicted in the Admiralty Tide Tables. Generally speaking the differences between the levels of highest astronomical tide and, say, the largest predicted tide in any year is rather small (i.e. a few centimetres). In practice, this difference is unimportant, at least in Scotland, when compared with the difference between predicted and observed tidal levels due to weather effects. As a very simple example, a static depression with a pressure 38 millibars lower than average can produce an increase of 0.3m in tidal level above that predicted. Such static barometric effects, however, are usually less important than dynamic ones.

A rapidly changing weather pattern will often produce short period fluctuations in atmospheric pressure, which in turn produce fluctuations of a similar timescale in the tidal curve. A good example is provided by the passage of a series of squalls. As a result, undulations in tidal level are caused, with a typical period of a few minutes. These undulations are usually called 'seiches', and on the open coast they normally present no great problems, since the associated changes in water levels, velocities and accelerations are small. However, in enclosed or partly enclosed bodies of water such as harbours, bays or sea lochs the periodicity of the seiches can cause a resonance which amplifies their effect. This rarely occasions any distress to coastal defences but can cause problems to moored ships.

The most important meteorological effects which alter water levels are generally known as 'storm surges'. Such surges result from the effects of wind stress on the surface of the sea. In shallow seas, such as the North Sea, a strong wind can cause a noticeable rise in sea level within a few hours. As one result, tidal levels at the coast can be increased (at both high and low water) until the wind abates. If the wind suddenly drops and then reverses in direction, the excess water held in an area by the wind can then be released, usually as one or more long waves. If such waves are amplified by a narrowing estuary, they can attain a significant amplitude and if the resulting surge arrives at a coast at the same time as the high water of an astronomical tide, the nett result can be devastating.

In the North Sea, such effects can regularly produce a "residual", i.e. a difference between predicted and actual water levels of a metre or so. In severe events, a "surge" can be produced, i.e. a long wave-like disturbance which can add several metres to the tidal level, although fortunately not often at high tide. "Negative surges" can also occur, for example under an anti-cyclone, producing much lower levels than expected.

It is often the combination of a surge and a predicted high tide which causes flooding or damage along a coast. Both the height of surges, and the time of their arrival relative to (predicted) high water are very variable. A considerable amount of research into such events has been carried out, with the main objective of predicting extreme tidal levels. Such predictions are usually expressed in a probabilistic manner, using the idea of "return periods". For example the 100-year (return period) tidal level is that level expected to occur or be exceeded only once, on average, in each century.

For sites where there is insufficient measured data, it is necessary to use numerical modelling to predict such extreme levels (by interpolation from nearby sites), or to "hindcast" tidal levels that have occurred in the past. This latter task is important if information on a particular severe event is required, for example to analyse the causes of flooding or of damage to coastal structures.

Tidal currents

The tides occurring around the coastline of Scotland also result in significant tidal currents, even in areas where the tidal range is small, e.g. off the coast of Islay. Where the shape of the coast allows the tide to fill and empty a large area during each cycle (e.g. estuaries, tidal inlets), the effects of the currents often dominate the hydraulic and sedimentary regime of the area. Even on an open, wave dominated coastline, such currents have a variety of effects. They act together with the waves to transport sediment more efficiently, both on beaches and over the nearshore seabed. As a result of this capacity to transport sediment, the tide can produce shifting banks of sediment which affect coastal processes. The currents also interact with the waves, altering their character, especially where they are similar to the wave propagation speeds. Finally, although the currents tend to be roughly equal on flood and ebb in most places, the small asymmetries can be fundamentally important in a large number of ways, particularly in the transport of fine-grained sediments (muds and clays), together with any adsorbed pollutants, for example heavy metals. In terms of sediment transport in the nearshore zone, the direction and velocity of currents acting at High Water Level may be more important than higher current velocities acting at mid tide. Similarly the tidal residual (vectorial displacement over the period of one tidal cycle) may also be important in the transport of nearshore sediments, particularly in estuaries.

While tidal levels vary slowly in space, and can be represented by a single value for each location at a specified time, tidal currents are much more complex. Very substantial changes in speed and direction can occur over a few tens of metres. Also, currents can change significantly with depth. In the open sea, such changes are often modest, i.e. a gradual reduction in speed below the water surface, but maintaining a consistent direction. However, in shallow water close to a coast, in estuaries, and in the vicinity of structures, the situation is often much more complex. Indeed flows can be in very different, sometimes entirely opposing, directions at the surface and near the seabed.

Waves and swell

The action of waves on the coastline is normally the dominating process influencing the littoral regime. The main wave influence on much of the Scottish coastline is from wind generated waves. Such waves have periods in the range 1-25 seconds, but in Scottish coastal waters the important range is usually between 4 and 20 seconds. The size and period of waves which strike a coast depend on the wind speed, its duration and the 'fetch', that is the unobstructed distance over the sea surface that the wind has travelled. On open coasts where the fetch is very large but the wind blows for only a short period, the wave height is limited by the duration of the storm. Beyond a certain limit, the total fetch length becomes unimportant. Where fetch lengths are restricted, e.g. by offshore islands, a short storm may produce the largest potential waves and any increase in the duration will not cause extra wave growth. Such waves are described as "fetch limited".

On oceanic shorelines, including some of the Scottish coastline (especially the exposed west and north coast), the situation is usually more complicated. Where both the fetch and durations are extremely large waves then become 'fully developed' and their height depends solely on the wind speed. In such situations the wave period usually becomes quite large, and long period waves are able to travel great distances without suffering serious diminution. The arrival of "swell', defined as waves not generated by local and/or recent wind conditions, presents a difficulty in wave forecasting which it is only now becoming possible to overcome, using for example a global wave forecasting model.

Swell waves are of nearly constant period and direction (although the height of successive waves does vary). Swell can be measured easily and accurately gauged "by eye", but is difficult to predict numerically. In contrast, waves generated locally (i.e. over a few hundred kilometres, during a day or so) are much more variable in direction and period. These waves are more difficult to measure, or gauge accurately by eye, but much easier to forecast numerically.

As waves approach the shoreline they are altered as shallow water processes become important. Around much of the UK this starts to affect waves in water depths of around 20m (more off the north and west coasts of Scotland, where larger wave conditions are experienced). In shallow water the main processes in the transformation of waves are shoaling, depth-refraction, current refraction, seabed friction, wave breaking, diffraction and reflection. In general terms this results in a decrease in wave heights as they travel into shallow water but little change in wave period. Whereas offshore wave conditions vary gradually in space, inshore wave conditions are normally site-specific with considerable variation often experienced over relatively short distances. Similarly around the coastline of the UK, offshore wave conditions are experienced from every directional sector. However, the range of wave directions experienced in shallow water will be much smaller and some offshore wave directions may be unimportant.

For coastal engineering purposes, both offshore and inshore wave conditions are normally defined in terms of the significant wave height, H_s (which is the average height of the highest one third of the waves in a given sea state), the wave period, T_m (which is the time taken for two successive wave crests to pass the same point), and the wave direction, θ.

3.4 Littoral processes

The concept of coastal cells is concerned with sediment movements in the littoral zone (see Figure 3). The rate and direction of such movements are influenced not only by the prevailing hydraulic processes, such as swell and wind waves and tidal, wind and wave induced currents, but also by the bathymetry and the physical characteristics of the beach and seabed (e.g. sediment size).

On a sand or shingle beach, the influence of the natural processes, particularly the wave action, will result in the beach attempting to attain an equilibrium profile. This profile will normally vary depending on the incident conditions. For example there is often a distinct summer/winter cycle where storm wave action in winter months draws beach material further down the beach to below the low water mark resulting in a flatter beach slope. This material is then transported back up the beach during the summer (resulting in a steeper beach slope) during milder wave conditions. Where there is little long term change in the beach morphology the beach system is said to be in dynamic equilibrium. In general, drawdown of the beach occurs at a much quicker rate, e.g. over the period of a single storm, than beach build-up, which may take a number of months. Hence, beach material may appear to have been eroded when it may simply be removed due to a recent storm with there being insufficient time for the material to be moved back onto the upper beach.

Where waves break obliquely at the coast a longshore current will be created in the surf zone which, when acting with the stirring action of the waves, will result in the longshore transport of material. Littoral drift is a dominant influence in shaping the coastline and is the major cause of coastal erosion (or accretion) particularly where the dynamic equilibrium of the drift regime is altered in any way (either due to natural changes or due to other external influences, e.g. human). On most of Scotland's beaches, sediment will move in both directions along a beach due to waves from different directions. However, it is normally the nett sediment transport rate and direction which is of greatest importance. A nett transport of material may be evident at the coastline, e.g. where there is a build up against a harbour breakwater, or a groyne over a length of time (years). However, it is often difficult to determine the direction and magnitude of any littoral transport confidently, particularly around the coastline of Scotland where the magnitude and direction of wave conditions are variable. To do so normally requires the use of numerical models which predict longshore transport using a time series of wave data. In certain situations, other hydrodynamic processes can cause littoral drift, either adding to or opposing the drift caused by waves breaking obliquely to the beach contours. These processes include tidal currents and longshore variations in breaking wave height. The former can be important when currents are still strong at high (and low) water, especially on straight coastlines (e.g. north of Aberdeen). The latter process is well demonstrated by the shelter provided by an offshore island. This provides substantial spatial variations in wave height, leading to a strong drift from the more active areas into the sheltered water.

In addition to an understanding of sediment movements, a knowledge of the inputs and outputs of sediment into the littoral regime is required. This is known as the sediment budget. It is important to know whether there is any fresh source of beach material being input to the system, e.g. from fluvial sources, cliff erosion or offshore deposits, or whether existing material is being reworked by coastal erosion. Similarly knowledge of whether material is being lost completely from the beach system, e.g. offshore, or if it is moved by wind action into a dune system, or whether it is accreting on the beach, is also important.

To assess the possible impacts and requirements of future coastal protection works, and to understand the likely future evolution of the shoreline, a quantitative understanding of these littoral processes is required.

3.5 Coastal defence, monitoring and management

There are two main types of coastal defence - "Coast Protection" where engineering works are used to protect an eroding coastline from further erosion, and "Sea Defence" where works are provided to prevent flooding of the coastal hinterland due to extreme wave and/or tidal conditions. In assessing existing defences along a frontage there are three main criteria which need to be examined:

- the structural condition of the defence,
- its capacity to prevent overtopping or flooding,
- the impact of the defence on the surrounding littoral regime.

The standard of protection provided by a section of coastal defence depends on the margin of safety it provides against structural collapse or unacceptable high overtopping discharge for example, both of which are highly influenced by the level and condition of the beach in front of the defence. Each of these criteria are inter-related with structural failure a consequence of the hydraulic forces as well as structural and geotechnical aspects. Overtopping and flooding, as well as depending on the severity of storm conditions, is also a function of the crest level of the structure and cross-sectional profile. Similarly the condition of the beach in the locality of the defence is a function of the sediment supply, hydraulic conditions and also of the type and design of the structure.

Construction of coastal defences, either to prevent flooding or to control coastal erosion, can have a variety of effects on the coastline and the development of beaches. Linear structures built along a frontage can have various detrimental effects on a beach. For instance, structures constructed in front of eroding cliffs or links areas can prevent the contribution of fresh material to the beaches, with resulting sediment starvation of the coast downdrift, known as downdrift erosion. Where wave action interacts with a linear defence, wave reflections from the structure can lower the level of the beach in front of it, and hence allow greater wave attack on the structure itself.

Of greater impact on the littoral regime is the effect of interrupting or altering the longshore transport of beach material, e.g. by the construction of a harbour breakwater or construction of a groyne system. The long term effects of either reducing or stopping all drift along a coastline can be an increase in erosion at beaches further along the coast due to sediment starvation.

3.6 Natural and cultural heritage

There are a number of statutory and non-statutory forms of designations which are used to protect terrestrial sites with natural and cultural heritage value. Statutory designations, or areas which have some form of 'custodial' ownership, have mechanisms which protect them, to a limited extent, from certain development or harmful activities. There is also a wide range of conservation legislation protecting individual habitats and species which may affect future shoreline management. Further information on natural heritage sites can be obtained from Scottish Natural Heritage with information on cultural heritage sites from Historic Scotland.

The range of national and international designations afforded to the coastal areas of Scotland of direct relevance to shoreline management, the designating organisations, and a short description of each taken from the Scottish Office discussion paper, *Scotland's Coasts* (Scottish Office, 1996), are detailed below:

Sites of Special Scientific Interest (SSSI) — Scottish Natural Heritage

Designated by SNH under the Wildlife and Countryside Act 1981 Section 28 to protect areas of important flora, fauna, geological or physiological features. Extensive parts of the coast are included within the SSSI network but the legislation only applies to land above MLWS. SSSIs provide the basis for other national and international designations e.g. NNRs and SACs. SNH requires to be consulted on developments, or notified of potentially damaging operations, which may affect the SSSI interest.

National Nature Reserves (NNR) — Scottish Natural Heritage

Declared by SNH under the National Parks and Access to the Countryside Act 1949 Section 16. NNRs are owned or leased by SNH or managed under agreement to protect and enhance their outstanding nature conservation interest. Public access may be controlled through bye-laws. NNRs are also SSSIs, and some have coastal frontage or are offshore islands.

Marine Nature Reserves (MNR) — Scottish Natural Heritage

Provision is made in the Wildlife and Countryside Act 1981 Sections 36 and 37 to designate marine areas to conserve their marine flora and fauna. This is the only statutory designation which specifically relates to marine areas below the low water mark. Designation procedures involve extensive consultation and protection is by bye-laws. There are currently no MNRs in Scotland but a voluntary Reserve operates at St Abb's Head in Berwickshire.

Local Nature Reserves (LNR) — Local Authorities/Scottish Natural Heritage

Section 21 of the National Parks and Access to the Countryside Act 1949, and Section 10 of the Local Government (Scotland) Planning Act 1982, give powers to local authorities in conjunction with SNH to establish Local Nature Reserves for their conservation and amenity value and for the public enjoyment of the countryside. They are controlled by bye-laws. To date three coastal LNRs have been established in Scotland.

Special Areas of Conservation (SAC) — Scottish Office

SACs are to be designated under the 1992 EC Directive on the Conservation of Habitats and Species. The special interest of SACs must be strictly protected. SACs, together with SPAs classified under the EC Wild Birds Directive (see below), will form a European-wide network of sites known as Natura 2000. The main aim of the network is to maintain the relevant species and habitats in a favourable conservation status. Coastal and marine sites are among the areas which, following consultations, are being proposed to the European Commission for SAC designation.

Special Protection Areas (SPA) — Scottish Office

The 1979 EC Directive on the Conservation of Wild Birds requires special measures to be taken to protect wild birds and their habitats, including the designation by the Secretary of State of Special Protection Areas to safeguard vulnerable species and regularly occurring migratory birds. Scotland is particularly important for cliff-nesting seabirds, waders and wildfowl. SPAs are subject to the same strict protection of their special interest as SACs.

Ramsar sites — Scottish Office

The Ramsar Convention requires wetlands of international importance to be protected to safeguard wetland habitats and species including those which contain large numbers of wildfowl. Several coastal or marine areas are designated or proposed Ramsar sites. The Secretary of State, on the advice of SNH, designates Ramsar sites and the Government has decided that as a matter of policy these sites should be accorded the same strict protection as for SPAs and SACs.

National Scenic Areas (NSA) — Scottish Natural Heritage

National Scenic Areas were introduced by circular in 1980 (amended in 1985) to safeguard areas of outstanding landscape importance as identified by SNH (formerly the Countryside Commission for Scotland (CCS)). Policies for protecting NSAs are set out in development plans and planning authorities are required to consult with SNH on specific categories of development. A number of NSAs incorporate part of the coast.

Natural Heritage Areas (NHA) — Scottish Natural Heritage

The Natural Heritage (Scotland) Act 1981 Section 6 makes provision for the designation of NHAs, although none has been introduced to date. These will cover extensive areas including the coast within which nature conservation, landscapes and cultural issues will be managed under a single integrated management plan which will be approved by the Secretary of State.

Areas of Great Landscape Value (AGLV) — Local Authorities

Under the provisions of Circular 2/1962, AGLVs are identified by local authorities in development plans with appropriate policies to protect areas of regional or local landscape importance. AGLVs vary in area and may include parts of the coast.

Environmentally Sensitive Areas (ESA) — Scottish Office (SOAEFD)

These are designated by the Secretary of State under the 1986 Agriculture Act to encourage landowners to manage their land to safeguard and enhance the nature conservation, landscape and cultural interest of the land for which a grant is available.

Marine Consultation Areas (MCA) — Scottish Natural Heritage

These are non-statutory areas introduced in 1986 where SNH wish to be consulted on developments, in particular fish farms, which are likely to have an impact on the marine environment. There are 29 sites within Scotland, most of which are on the West Coast or the Islands.

Regional Parks and Country Parks — Local Authorities

These are promoted by the local authorities under the provision of Section 48 of the Countryside (Scotland) Act 1967 to provide informal outdoor recreation and to protect local landscape and amenity for the enjoyment of the public. Country parks are relatively small areas used intensively for informal recreation. Regional parks are extensive areas where existing land use continues but also accommodates recreational activities. Some of these parks incorporate coastal areas.

RSPB Reserves — Royal Society for the Protection of Birds

Private reserves owned by the RSPB where the main interest is ornithology but where there are often other important conservation interests.

Scheduled Monuments — Historic Scotland

Ancient monuments surviving in both town and country are tangible reminders of Scotland's long history. Because of the evidence they can provide about Scotland's past many ancient monuments are given legal protection against deliberate or accidental damage or destruction by being "scheduled". A scheduled monument is a monument which the Secretary of State considers to be of national importance and has included in a set of records (known as the Schedule) maintained by him under the Ancient Monuments and Archaeological Areas Act 1979.

4 Cell 2 - Information sources

4.1 General

Information on the physical characteristics and coastal regime is available from a variety of sources and organisations. The purpose of this section is to provide general details on the availability of such information and data sources of relevance to shoreline management. Further, site specific information, particularly on littoral processes and coastal defences, is contained within each of the sub-cell sections in Chapter 5.

Two general sources of information exist for this coastline. The UK Digital Marine Atlas (UKDMAP) which was developed by the British Oceanographic Data Centre, Birkenhead provides a reference database of the marine environment for the whole of the UK. It provides general information on a wide range of subjects including geology, hydrography, conservation and ecology. A review of information relating to the natural environment, the current protected status of coastal and marine habitats, communities, species and activities which have an effect on the North Sea coast is detailed within *The Directory of the North Sea Coastal Margin* (Doody et al, 1991) and in *Coasts and Seas of the United Kingdom: Region 3: North East Scotland - Cape Wrath to St Cyrus* (Barne et al, 1996); and *Region 4: South East Scotland - Montrose to Eyemouth* (Barne et al, 1997).

Details of physical oceanography and meteorological (Metocean) data collected around the British Isles on behalf of the UK energy industry is summarised in a report by Metocean (1994). This includes details of organisations who have collected information on winds, waves, currents, water levels and other associated parameters. Further information sources of physical data are detailed in the following sections.

4.2 Geology and geomorphology

The geology of the east coast of Scotland has been studied in detail in several studies such as, *British Regional Geology: The Midland Valley of Scotland* (Cameron & Stephenson, 1985) and *British Regional Geology: The Grampian Highlands* (Stephenson & Gould, 1995).

These reports reference a large number of more detailed localised studies conducted on the east coast. The British Geological Survey have also produced a series of solid and drift geology maps the availability of which is detailed below:

Table 2 Cell 2 - Available geological maps

Map No.	Map Name	Solid/Drift Geology	Scale
48E	Cupar	Solid/Drift	1:50,000
48W	Perth	Solid/Drift	1:50,000
49	Arbroath	Solid/Drift	1:50,000
57	Montrose area (out of print)		
67	Stonehaven	Solid/Drift	1:63,360
77	Aberdeen	Solid/Drift	1:50,000
87E	Peterhead	Solid/Drift	1:50,000
97	Fraserburgh	Solid/Drift	1:50,000

A 1:625,000 scale Quaternary geology map covering the area is also available.

The Geological Conservation Review was a 12-year research programme initiated by the Nature Conservancy Council in 1977 to identify the key onshore earth science sites in Great Britain using available survey and research information. Site classification was completed in 1989 and the review is currently being published through a series of approximately 40 volumes, 14 of which are now available.

The geomorphology of the east coast of Scotland has been studied in detail in several studies, the main texts being *The coastline of Scotland* (Steers, 1973); *The beaches of Fife* (Ritchie, 1979); *The beaches of Tayside* (Wright, 1981) and *The beaches of north east Scotland* (Mather et al, 1978). Other, more localised, studies have also been conducted. These include a detailed study of the whole of the Tayside coastline in 1987 (Caledonian Geotech, 1987) and by Mitchell (1997), hydraulic and littoral studies at both Montrose and Aberdeen beaches (HR Wallingford, 1993b & 1988a&b), an inventory of the geomorphological resources of the Dee, Don and Ythan Estuaries (Stapleton and Pethick, 1996), a survey of the coastline of Grampian (Hay, 1980), and a large number of geomorphological studies at the Sands of Forvie. Further published information is detailed in the bibliography.

4.3 Bathymetry

The bathymetry off the east coast of Scotland is illustrated in detail on the following Admiralty Charts:

Table 3 Cell 2 - Available Admiralty Charts

Chart No.	Location	Scale
190	Montrose to Fife Ness	1:75,000
210	Newburgh to Montrose	1:75,000
213	Fraserburgh to Newburgh	1:75,000
1407	Montrose to Berwick	1:200,000
1409	Buckie to Arbroath	1:200,000
1438	Harbours on the east coast of Scotland	Various
1446	Aberdeen Harbour	1:20,000& 1:7,500
1481	River Tay	Various

The charts are produced by the Hydrographic Office, Taunton, and also include information on tidal streams, tidal levels and other information of use to the navigation of sea vessels.

4.4 Wind data

The east coast is well served with anemometer records with winds having been recorded (and the information passed to the Met Office) at five coastal (or near coastal) locations within Cell 2, Table 4 and Figure 6. The wind recorders at Leuchars and Inverbervie are equipped with Semi-Automatic Meteorological Observing Systems (SAMOS) which produce wind statistics continuously for immediate archiving. The recorders at Dyce and Peterhead are equipped with Digital Anemograph Logging Equipment (DALE), which logs wind data onto magnetic tape, which is sent to Bracknell for incorporation into the Climatological Data Bank there. The recorder at Mynefield uses a graphical recorder, which has to be hand-analysed to provide suitable data for archiving.

Table 4 Cell 2 - Availability of wind data

Location	Period covered	Anemometer Type
Leuchars	01/70 - Present	Analysed anemograph from SAWS/SAMOS/CDL station
Mynefield	09/70 - Present	Data on Metform 6910
Inverbervie	unknown	Analysed anemograph from SAWS/SAMOS/CDL station
Dyce	01/70 - Present	Digital Anemograph Logging Equipment (DALE)
Peterhead Harbour	02/79 - Present	Digital Anemograph Logging Equipment (DALE)

4.5 Tidal data

In the UK, the most reliable measurements of tidal levels are from the "A-class" gauges - a national network set up and maintained by the Proudman Oceanographic Laboratory (POL) at Bidston, Merseyside. In addition, it is often possible to obtain local data from "private" gauges, (e.g. owned and operated by organisations such as port/harbour authorities).

The only A-class tidal gauge within Cell 2 is at Aberdeen, Figure 6. Tidal gauges, which are not part of the A-class network, are operated by the Port Authorities at Dundee and Montrose. Long term measurements from these gauges have been analysed to produce "harmonic constants". These are used to make local tide predictions as published in the Admiralty Tide Tables (and on the Admiralty Charts), Figure 6, and can be used to provide local tide predictions at any site, either by POL, or other organisations who have obtained the relevant computer programs to make such predictions. It should be realised, however, that the tidal predictions derived for these sites may not be as reliable as those from an A-class gauge.

Information on mean sea level can be obtained from the Permanent Service for Mean Sea Level (PSMSL) which is located at the Bidston Observatory in Birkenhead. This was set up in 1933 and is responsible for collecting monthly and annual mean values of sea level from approximately 1450 tide gauge stations around the world. The contents of the PSMSL data set are described in a report *Data holdings of the PSMSL* (Spencer & Woodworth, 1993) which can be obtained from the Bidston Observatory. Within Cell 2 mean sea level is recorded at Dundee and Aberdeen.

Actual tidal levels, however, can and often do vary significantly from those predicted using harmonic analysis due to meteorological effects (surges) (see Section 3.3). The UK Met Office Storm Warning Service operates a surge prediction model provided by POL. This has a 12km spatial resolution around the coast of the UK, and can provide information on surge conditions offshore. To provide predictions at the coastline a more detailed numerical model would be required. HR Wallingford have conducted localised tidal modelling in St Andrews Bay (HR Wallingford, 1992a & b) and between Lunan Bay and Inverbervie (HR Wallingford, 1995). A numerical tidal modelling study of the tidal regime around Cairnbulg Point was conducted as part of the Fraserburgh Long Sea Outfall feasibility study (Binnie and Partners, 1991). Further details of the known models are provided in Table 5:

Table 5 Cell 2 - Tidal modelling studies

Cell	Location	Study	Contact
2a	Tay Estuary (Fife Ness to Arbroath)	Tidal flow modelling Water Quality Modelling	HR Wallingford
2b	Montrose (Lang Crag to Inverbervie)	Tidal flow modelling Sand transport modelling	HR Wallingford
2d	Fraserburgh (Troup Head to Peterhead)	Tidal flow modelling Water Quality Modelling	Binnie & Partners

A number of studies have been conducted into extreme (surge) water level predictions (e.g. Graff, 1981; Woodworth, 1987; Coles & Tawn, 1990). The latest research into trends of extreme sea levels (Dixon & Tawn, 1994) provides a site by site analysis from the A-class tide gauge network of extremes around the coast of the UK. This research has been extended to produce a spatial analysis of extreme water levels every 20km around the UK mainland coast (Dixon & Tawn, 1997) and so includes the coastline of Cell 2. In practice, referring to these papers, or similar papers in the future, is likely to be the method used most often by coastal managers to determine extreme water levels in their area.

The Admiralty have always provided information on tidal currents to assist in navigation. The Admiralty Charts usually have a selection of "Diamonds", i.e. locations indicated on the chart by a diamond symbol, with accompanying lists of current speeds at that point throughout the tide. In UK waters, this information is given for both Spring and Neap tides. The currents are usually "depth-averaged", i.e. an average value of the speed throughout the water column.

In addition the Admiralty also produce "Tidal stream atlases" with the offshore zone of Cell 2 covered in the *North Sea: Flamborough Head to Pentland Firth* (Hydrographer of the Navy, 1963). These show the currents over a wide area at various states of the tide. The flows are represented by arrows, annotated with the approximate speeds (again for Spring and Neap tides). However, this information is aimed at those navigating ships; it is rarely of much use in very shallow coastal waters or away from the main channels in estuaries.

Tidal current measurements are normally made over relatively short periods of time, (usually less than 1 year), often in connection with a particular study. There are two main sources of such data. Firstly the British Oceanographic Data Centre have a digital inventory of current meter data around the British Isles. This holds either actual information, or details of the location of such data collected by a wide range of organisations, and is available directly from BODC. The other source is from commercial survey companies carrying out site-specific studies. The BODC inventory details the locations of a large number of current meter recordings. This information has not been recorded within this report, but the digital directory is available directly from BODC. No information was obtained of any recordings by commercial survey teams within this cell.

4.6 Wave data

Information on offshore wave conditions can be obtained from two sources, either from measured wave data or from synthetic wave data generated using numerical models. The only detailed record of instrumentally recorded wave data in Scotland is the MIAS catalogue (MIAS, 1982) which was compiled in 1982 by the Institute of Oceanographic Sciences. The British Oceanographic Data Centre (BODC) have since taken over the cataloguing of measured wave data and are presently producing an updated digital version. Wave recording is conducted occasionally by commercial organisations normally in connection with marine construction projects, e.g. harbour developments.

Measured offshore wave conditions are detailed in Table 6 and the locations shown in Figure 6. The records listed in Table 6 contain only details of wave height and period. No details of the wave direction were recorded. It is unlikely that this wave information will be in a suitable format to be of much use in coastal management. A more effective use of this data would be in the calibration of wave numerical models which can be used to predict wave climates and extreme conditions. Details of the recorded wave information can be obtained from BODC.

Table 6 Cell 2 - Recorded wave information

Location	Lat/Long	Period covered	Mean Water Depth (m)	Contact
North Carr Lightvessel	56°18'18"N 002°32'00"W	June 1969 to June 1973	42m	MIAS
Abertay Lightvessel	56°27'24"N 002°41'06"W	1972 to present	unknown	Dundee Harbour Trust (MIAS)
Peterhead	57°30'N 001°47'W	17 Jan 1973 to 15 Mar 1979	unknown	North of Scotland Hydro-electric Board (Pitlochry Research Laboratory) (MIAS)
Peterhead	57°29'N 001°45'W	26 Feb 1976 to 24 Aug 1976	35m	IMCOS Marine Ltd (MIAS)
NNE of Kinnairds Head	57°55'48"N 001°54'06"W	23 Feb 1980 to present	unknown	MIAS

Information on wave conditions can also be obtained from the VOS (Voluntary Observations from Ships) archives. Many ships of passage make regular observations of wind and wave conditions as part of their routine duties. This information is collected worldwide and collated by the UK Meteorological Office. The records include date, time, location, wind speed and direction, significant wave height (H_s), zero-crossing period (T_m) and wave direction. Although not scientifically measured, VOS records have been found to be a useful source of data where there has been a large number of records spanning many years, e.g. major shipping lanes. VOS data is available in the form of monthly, seasonal and annual frequency tables of wave height and period in 30° sectors for sea areas specified in 1° latitude and longitude squares. Details of the density of VOS data can be supplied by the Met Office.

When using VOS data it is important to ensure that the selected area is large enough to contain sufficient data in each sector for a reliable analysis of extreme conditions, but small enough to ensure that conditions are representative of the region of interest. In addition, for an analysis based on VOS observations to be valid, it is necessary to ensure that the exposure of the location of interest is the same as that of the VOS area used, for the direction sectors of interest.

In many locations offshore wave prediction using numerical modelling techniques is difficult. Around much of the UK coast it is necessary, as a minimum, to have a model which can predict the generation of waves over a substantial part of the sea or ocean, and then to "follow" those waves as they develop into swell. A number of such numerical models exist, all run by national meteorological offices, or other governmental departments. In the UK, the most convenient model to use is the Meteorological Office European Wave Forecasting Model.

Two surface wave models are run at present on an operational (daily) basis at the UK Meteorological Office. These models are the result of an evolving series of such models, in use since 1976. They were designed primarily for offshore application, for example in ship routing and operation of offshore structures. The model calculations are carried out on a polar stereographic grid, whose exact spacing therefore varies from one latitude to another. The European Wave Model (grid spacing about 30km) is nested within the Global Model (grid spacing about 150km) from which it takes its boundary wave conditions. The 30km grid size means that shallow water effects are not well represented in the model, and grid points closest to the land are not used for prediction purposes. Before use at the shoreline, the model predictions therefore need to be transformed from 20-50km offshore to the coast (see below).

The models are run twice daily, driven by wind fields extracted from operational global weather forecasting models. They produce wave forecasts from 12 hours prior to the run-time ("T") up to 36 hours ahead, at 3 hourly intervals. As well as noting the time, date, latitude and longitude, each forecast gives the wind speed and direction, and the significant wave height, mean wave period and wave direction for the separate wind-sea and swell components and overall. The data from T-12 hours to T+0 hours is permanently stored in an archive, whilst the data from T+0 hours to T+36 hours is immediately disseminated for forecasting purposes. Sea state observations from fixed buoys, oil platforms, Ocean Weather Ships, and more recently satellite wave measurements, are used for real-time "calibration" of the models, and also for periodic validation. The archived information provides a very useful "synthetic" offshore wave climate. Figure 6 shows the grid point locations offshore of Cell 2.

Modern numerical methods are capable of accurate predictions of "wind-sea" for offshore areas, especially if there is good quality, sequential wind data available to provide the basic input conditions. This technique has been used at a number of locations offshore of Cell 2, Table 7.

The final stage in numerical wave prediction is to transform such offshore wave information into corresponding nearshore conditions. This may be carried out for a few offshore conditions (e.g. waves expected to occur only in exceptional storms), or for a whole wave "climate". For further details of the range of numerical techniques available, the reader is referred to the recent report by Dodd and Brampton (1995). However, in outline all such models start from a digital representation of the water depths between the offshore point at which waves are predicted, and the stretch of coastline under consideration. A number of alternative techniques are available that calculate the way that wave energy propagates shoreward; they all include the processes of refraction and shoaling, and many can include other effects such as frictional dissipation, the shelter provided by offshore islands or headlands, the effects of tidal currents or the continuing growth of waves as they travel across the area being modelled. The accuracy of such transformation methods is generally good, provided an appropriate model has been chosen. The inshore wave climate has been derived at a number of locations along the coastline of this cell. These locations are detailed in Table 7.

Table 7 Cell 2- Sources of numerically modelled wave conditions

Location	Offshore/Inshore Position	Period	Mean water depth (m)	Wave data	Contact
On a regular grid 0.25° lat. by 0.4° long	Offshore: First point is normally less than 20km from the coast	1986 onwards	variable	Wind, swell and total sea climate and extremes	UK Met Office or HR Wallingford
Barry Buddon	Offshore: 56°25'15"N 2°38'W Inshore: 56°29'30"N 2°42'10"W 56°28'45"N 2°42'10"W 56°28'20"N 2°41'30"W	11 years	 > 20mCD < 5mCD < 5mCD < 5mCD	Wave climate and extreme wave conditions at all positions	HR Wallingford
Montrose	Offshore: 56°42'N 2°20'W	10 years	~ 30mCD	Wave climate and extreme wave conditions	HR Wallingford
Stonehaven	Inshore: 56°57'37"N 2°11'30"W	Unknown	Unknown	Wave climate and extreme wave conditions at all positions	HR Wallingford
Aberdeen	Offshore: 57°9'N 1°59'W Inshore: 3 positions along Aberdeen beach frontage	Unknown	 ~ 40mCD ~ 5mCD	Wave climate and extreme wave conditions at all positions	HR Wallingford
Peterhead	Offshore: 1 position offshore of Peterhead Harbour entrance	unknown	unknown	Extreme wave conditions	HR Wallingford

4.7 Natural and cultural heritage

Information on statutory designations and protected sites of natural heritage importance, and on certain non-statutory sites, is provided by Scottish Natural Heritage. Within Cell 2 the number of designated natural heritage sites is given in the Table below (see Section 3.6 for definitions):

Table 8 Cell 2 - Natural heritage designations

Designation	Number	Designation	Number
SSSI	30	NSA	-
NNR	3	NHA	-
MNR	-	AGLV/ARLS/ASV	10
LNR	4	ESA	-
SAC	1	MCA	-
SPA	3 (proposed)	RSPB	2
RAMSAR	5 (proposed)	LWT	3

Note: Data correct to September 1996. Supplied by Scottish Natural Heritage.

The location of Sites of Special Scientific Interest is shown in Figure 7 with further information detailed in Appendix 1. Other natural heritage designations are shown in Figure 8. These data are accurate to September 1996.

Advice on historical and archaeological matters is provided by a number of organisations which are detailed in the following table:

Table 9 Cell 2 - Information sources for sites of cultural heritage

Advice or information on:	Contact
Scheduled monuments	Historic Scotland
Designated wrecks	Historic Scotland
The protection & management of sites and monuments	Historic Scotland or Regional Archaeologist
Sites or monuments already known	Historic Scotland/Regional Archaeologist RCAHMS
Archaeological remains discovered during development	Historic Scotland/Regional Archaeologist
The discovery of a site	Regional Archaeologist/RCAHMS
An isolated artefact find	Regional Archaeologist/National Museums of Scotland/Local Museum
Damage to a scheduled monument	Historic Scotland
Damage to an unscheduled monument	Regional Archaeologist

Adapted from *Archaeological and Historical Advice in Scotland* available from Historic Scotland.

The Royal Commission on the Ancient and Historical Monuments in Scotland (RCAHMS) maintains a GIS database (National Monuments Records of Scotland, NMRS) with the locations of scheduled archaeological and historical sites. Only the location of sites within 50m of the coastline was requested from the RCAHMS in this study. However, the RCAHMS advised that to locate all coastal sites would require a resolution of 500m from the coastline. Figure 9 shows the relative density of scheduled archaeological and historical sites within 500m wide by 10km long strips along the coastline of Cell 2. Because of the low resolution these will include a large number of sites which are not truly coastal. Only where more detailed surveying has been conducted can an assessment of the number of coastal sites be determined, but such a study does not appear to be available for any part of the coastline in Cell 2. There are also a large number of sites, e.g. Listed Buildings, which do not appear in the NMRS database. Appendix 2 shows the actual locations of scheduled sites within 500m of the coastline obtained from the NMRS database.

5 *Cell 2: Fife Ness to Cairnbulg Point*

5.1 Introduction

Cell 2 has been defined, (HR Wallingford, 1997), as the coastline between Fife Ness, in the south, and Cairnbulg Point, in the north. Both boundaries are at a significant change in the orientation of the coastline. It is unlikely that significant amounts of beach material will be transported across either of these boundaries. For the purposes of future management, this cell has been further divided into four sub-cells, the boundaries of which are presented in Figure 5. These sub-cell boundaries are located where significant changes in the character of the coastline occur, e.g. from a sand to a cliff dominated coastline such as at Milton Ness. All of the sub-cell boundaries identified are relatively sediment 'tight', i.e. there is little evidence of longshore drift of beach material crossing the boundaries. The River Tay Estuary is contained within one sub-cell. For the purpose of this study the Tay Road Bridge is defined as the upstream boundary of the sub-cell. Within the sub-cells further possible boundaries, such as individual beach units, can be identified. For instance there is unlikely to be any significant interchange of beach material between the Aberdeen to Ythan beach system and the beaches north of Peterhead. The locations of these "semi-independent beach units" are shown in the relevant littoral process maps.

Section 5.2 describes where further information of relevance to shoreline management on this coastline can be obtained. Sections 5.3 to 5.6 describe the coastal regime within Cell 2.

5.2 Cell 2: Physical characteristics

5.2.1 General

The characteristics of Cell 2 and processes occurring within it are described under the headings of Geology and geomorphology, Hydraulic processes, Littoral processes and Coastal defences and monitoring.

The geology and geomorphology of the coastline of Scotland is an extremely complex topic with few detailed texts on the subject. Only a brief description of the solid geology and geomorphological features is presented within this report. Drift deposits occurring at the coastal edge in Cell 2 are shown in Figure 10.

The dominant hydraulic processes, i.e. the tides, currents and waves are described. Tidal elevations within each sub-cell are described and, where known, details of any surge information. The direction of the main tidal currents and magnitude of tidal velocities are also detailed. Any areas where significant tidal flooding occurs are also noted. Information on tidal currents within Cell 2 is also summarised in Figure 11. The offshore wave climate (both total sea and swell) has been predicted from the Met Office Wave Model along with a range of extreme offshore wave conditions. The offshore total sea and swell climates to the region to the east of the Tay Estuary are shown in Figures 12 and 13 respectively and for the region to the east of Aberdeen in Figures 14 and 15. These wave climates are representative of the general offshore wave climate i.e. they do not represent one particular location. Where possible the dominant nearshore processes which affect the transformation of offshore to inshore wave conditions are also described.

The next section within each sub-cell describes the main littoral processes. The dominant beach sediment sources and sinks are described. Where possible the main nett longshore transport directions are detailed with an indication of the dominant forces causing this drift. Known areas of long term nett erosion and accretion are also described. Where more detailed engineering studies have been conducted, these have been referred to for any indication of erosion or accretion rates. Locations where man-made development in the coastal zone is known to have altered the littoral regime are also described. Details of the foreshore and hinterland characteristics are shown in the relevant figures for each sub-cell along with the dominant littoral processes. Locations where maintenance dredging is conducted are listed, and where possible, an indication of dredging rates and the source of siltation is provided.

The final section details the location, type and influences of coastal protection work. Where possible a brief indication of the present state of the defences and any significant impacts on the coast due to these works is outlined. Locations where beach monitoring or coastal surveys have been conducted are presented and, where possible, details of the length of such records and monitoring authorities are given. Details of existing coastal defences and locations where regular monitoring is conducted are shown in the relevant figures for each sub-cell.

5.3 Sub-cell 2a - Fife Ness to Deil's Head

5.3.1 Geology

Between Fife Ness and the northern coastline of the Eden Estuary, the underlying geology consists of sedimentary rocks deposited during the Dinantian (early Carboniferous period), around 340 Ma. Two main rock lithogies formed during that time. The older underlying Calciferous Sandstone measures consist of pale sandstones, grey mudstones, siltstones and marine limestones. Overlying these strata is the younger Lower Limestone Group which is made up of sandstones, mudstones, limestones and coals. A number of vents of former volcanoes occur within this region. The most notable occurrence of such igneous rock on the coastline is to the south east of St Andrews within the St Andrews to Craig Hartle SSSI.

A band of Upper Devonian Old Red Sandstone runs in a north east to south west orientation across Fife outcropping at the coast by Leuchars. Further north the underlying hard geology to Tayport and from Monifieth to Arbroath is Lower Devonian in age. To the west of Tayport and around the Broughty Ferry area, igneous rocks of andesitic and basaltic lavas and tuffs occur.

During glaciation, ice flowed outwards over this area in an easterly direction from the landmass. The last glacier to affect this part of the Scottish coastline retreated around 15,000 years BP. The major effect of this glaciation, in terms of the coastal geomorphology, was the widespread accumulation of glacial deposits. These deposits were laid down both directly by the retreating ice sheet, such as the boulder clay deposits which cover much of Fife and Tayside, and indirectly due to fluvioglacial meltwater deposits. Extensive areas of sands and gravels were deposited around Wormit, the northern coast of Fife and around Barry Buddon.

Reworking of this material by winds, waves, tides and postglacial sea levels has provided the beach material and fashioned much of the hinterland geomorphology evident today. Much of the low lying coastline of this sub-cell was inundated during the postglacial marine transgression when relative sea levels were higher than today, producing the raised beach areas which back a high percentage of this coastline. Such features are evident between Fife Ness and Boarshill, at St Andrews, along the southern coastline of the Eden estuary, the north bank of the River Tay to the east of Broughty Ferry and between Carnoustie and Arbroath. As sea levels began to fall relative to the land, approximately 6000 years ago, large areas of intertidal sands dried out and were blown inland forming the links areas of Tentsmuir and Barry Buddon.

5.3.2 Hydraulic processes

The tidal regime is semi-diurnal in character with a spring tidal range of 4.3m at Arbroath and 4.5m at Tayport, Figure 11 and Table 10. North of the Tay estuary the flood and ebb tides are rectilinear, flowing parallel with the coast in a south east and north west direction respectively. Offshore of the Tay estuary the flood current flows in a southerly direction across the mouth. The tide rotates in a clockwise direction with a maximum spring tidal stream of around 1.2 knots ($0.6ms^{-1}$). Within St Andrews Bay tidal currents are extremely low, generally less than $0.2ms^{-1}$, (HR Wallingford, 1992b). Wind generated currents have a significant effect on both the current speed and direction within the bay.

Table 10 Sub-cell 2a - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	ODN to CD (m)
River Tay Bar	2.3	-2.1	4.4	1.3	-1.0	2.3	+2.90
Newburgh	2.8	-1.2	4.0	1.7	-0.8	2.5	+1.30
Dundee	2.4	-2.2	4.6	1.4	-1.0	2.4	+2.90
Arbroath	2.2	-2.1	4.3	1.3	-1.0	2.3	+2.80

In Table 10 the tidal elevations are quoted relative to Ordnance Datum Newlyn (the standard land based datum). The conversion to the local Chart Datum (where known) is shown in the final column.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. Within these studies there are no locations in sub-cell 2a where extreme water level predictions were made.

The latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water level predictions depend upon the year of interest, allowing for trends in mean sea level rise, and hence have not been reproduced within this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Within the Tay estuary, current velocities can be high with an Admiralty Diamond indicating a peak Spring flood velocity of 2.3 knots (1.15ms^{-1}) to the south west of Buddon Ness. Tidal flows are restricted around low water by the intertidal sand banks of Gaa and Abertay Sands. River flows can have a significant effect on the tidal regime of the area causing complex patterns of water movement. The river has both the largest average fresh water discharge, and highest recorded flow, of any river in Britain. Studies of tidal patterns within the Tay estuary have been conducted by members of the Tay Estuary Research Centre, (Buller, McManus & Williams, 1971) and in the estuary and St Andrews Bay by HR Wallingford (1992a & b). In comparison the flows into and out of the Eden estuary are much lower.

The offshore total and swell wave climate for the region to the east of the mouth of the River Tay is shown in Figures 12 and 13 respectively. The dominant wave conditions approach from between 20°N and 60°N. However, extreme wave conditions (greater than 4m) can be experienced from all of the easterly sector. Wave conditions are less frequent from the south easterly quartile than from the north-east. Extreme wave total sea wave conditions have been predicted from the Met Office Wave Model and are detailed in the table below:

Table 11 Total sea extreme significant wave heights

Return Period (Years)	Significant wave height (m)
1	6.23
10	7.62
100	8.95

Swell waves contribute a significant proportion of the total wave energy experienced in this region. The largest percentage of this swell will have been generated within the Norwegian Sea, with some heavily diffracted swell from the North Atlantic also contributing. Little swell is experienced from the south east. Extreme swell wave heights for this offshore region are detailed in Table 12.

Table 12 Swell wave extreme significant wave heights

Return Period (Years)	Significant wave height (m)
1	3.56
10	4.49
100	5.36

Depending upon the orientation of the coastline, inshore wave conditions approaching from between about 30°N to around 180°N have a significant effect on the coastline. Numerical modelling of the offshore wave climate offshore from Barry Buddon, (HR Wallingford, 1989), has shown that storm wave conditions can occur from any direction where fetch lengths extend into the North Sea. At the coastline, the level of exposure to wave attack varies somewhat within the sub-cell depending on the wave direction. For instance, Tentsmuir is sheltered somewhat from north east storms by Buddon Ness with Fife Ness sheltering St Andrews Bay from southerly wave attack, (Ritchie, 1979). Offshore banks at the mouth of the Tay estuary such as Abertay and Gaa Sands will also have an effect of reducing the wave conditions reaching the shoreline.

5.3.3 Littoral processes

The foreshore and hinterland characteristics occurring in Sub-cell 2a are shown in Figure 16. The dominant littoral processes are dominated by wave and tidal currents and are shown in Figure 17.

The vast quantities of beach material occurring within this sub-cell were deposited by the main river systems during and at the close of the last Ice Age when meltwater from glaciers inland produced much larger flows and transport of sediment than experienced today. In postglacial times these deposits have been reworked by wind, waves and tidal currents as relative sea levels first rose and then fell again to form the present beaches and coastal hinterland. There is a high potential input of beach material into the active coastal system from such postglacial deposits, such as those at Tentsmuir and Barry Links. Although some reworking (i.e. coastal erosion) is occurring, in relative terms the input from such sources is minimal. Fluvial input of beach material from the River Tay is unlikely to be significant with much of this (fine) material either depositing on the intertidal sand banks found within the Tay estuary, or being flushed further offshore.

Both wave and tidal current influences have a significant effect on the longshore transport of sediment. Figure 16 shows the nett longshore transport direction of beach material within the sub-cell. Outside the Tay estuary, i.e. on the open coast, longshore transport is wave dominated. Such effects are responsible for the northward movement of material along the north Fife coastline and the southerly nett movement between Arbroath and Buddon Ness. Within the Tay estuary, and near its mouth, longshore drift can also be influenced by the strong tidal currents, particularly lower down the beach.

Little erosion of the coastal edge occurs south of St Andrews apart from slight undercutting of the dune edge at the small beach areas of Balcomie and Cambo under storm conditions. Reliable maps have been available from the eighteenth century indicating that there has been a build up of sand on the seaward side of the Pilsmuir links area, (Ritchie, 1979; HR Wallingford, 1994). Along the Eden side of the links, the tendency has been for erosion to occur. This erosion/accretion pattern is associated with the north eastward movement of Out Head. It is not clear whether the beach accretion caused the channel to move northwards or vice versa. In the last 40 years or so, there has been little advance in the position of the eastern shoreline with small localised areas of erosion now occurring, probably linked to human activities i.e. the *ad hoc* coast defence works. At the mouth of the Eden, the channel position is still extremely dynamic and complex, (Jarvis & Riley, 1987) with the erosional/accretional pattern of the sand banks within the estuary variable. The Tentsmuir system is generally thought of as an area of accretion. Map analysis since the mid 19th century of the coastal edge is presented in *The Beaches of Fife Report* (Ritchie, 1979) and shows the coastal edge prograding particularly at the northern end where the sand banks at the mouth of the Tay are accreting sand. Accretion at Tentsmuir Point is also thought to be linked to alterations in the tidal banks seawards of the mouth of the Tay, which in turn are connected with the unpredictable meandering of the main channel. Localised areas of erosion of the frontal dune face do occur along the eastern facing beach related to individual storm events. This does not appear to be a long term problem.

Much of the Tayside coastline experiencing erosion is now protected. Between Monifieth and Broughty Ferry, waves generated within the North Sea result in a westerly movement of sand sized beach material. More frequent (but smaller in wave height) wave conditions from the south west result in an easterly movement of beach material. However, the nett wave induced movement appears to be to the west on the upper beach. Ebb tidal currents, acting lower down the beach appear to recycle beach material transported towards Broughty Ferry Castle back along the lower beach to the east. Groynes protect various lengths of the frontage along the Monifieth and Barnhill frontage. These groynes are effective but have resulted in much of the beach material being trapped within the groyne bays causing the immediate coastlines outwith the groyned areas to be denuded of material (i.e. downdrift effect). At the western end of Monifieth serious erosion of the reclaimed land at the caravan park is presently occurring with a vertical 2m scarp face cut into the bank. At Monifieth, little now remains of the dune ridge along the length of the road leading to the caravan park. The sand beach is also extremely narrow along this frontage, with mean high water reaching the base of the frontal dunes, which have now largely been protected by a rock revetment and rock rip-rap.

Historically the general shape of Barry Links has changed very little within the last 200 years, (Steers, 1973). A detailed study of the littoral processes was conducted by HR Wallingford (1989) in connection with erosion of the eastern flank of Buddon Ness. Digital Ground Modelling of the nearshore zone using hydrographic surveys between 1969 and 1988 indicated that sea bed material is transported southwards from the northern part of Carnoustie Bay and onto Gaa Sands. It would then appear that a large anti-clockwise eddy on the ebb tide tended to recirculate material from Gaa Sands onto Gaa Spit and towards the shoreline.

On the intertidal beach, historical map analysis (Mitchell, 1997) along the eastern coast of Buddon Ness has indicated that substantial seaward movement of the MHWS line occurred between the 1865 and 1959 surveys with erosion and a landward retreat of the MHWS mark since 1959. Analysis of beach levels along the east facing Barry Sands, (HR Wallingford, 1989) indicated nett erosion at the northern end with associated accretion occurring towards Buddon Ness. This erosion is attributed to wave effects and changes in the bathymetry within Carnoustie Bay. In general there has been a deepening within the northern part of Carnoustie Bay and shallowing of the depths on the north flank of Gaa Spit to the east of Buddon Ness. This is due to a combination of wave and tidal effects, with material transported by currents along the western facing beach at Barry Links being deposited mainly along Gaa Spit. With the increase in size of these sand banks, the shelter from waves from the south is increased.

The coastal frontage at Carnoustie is also experiencing long term erosion. The nett longshore drift of beach material is dominantly towards Barry Sands. To the north of Carnoustie the coastline is provided some protection by the rocky nature of the foreshore. Hence the supply and longshore drift rate of beach material is likely to be somewhat less than that experienced along the (less protected) Carnoustie frontage leading to a shortfall in the sediment budget. Beach material is also fed back into this system from Gaa Spit but the movement of this material onshore is likely to be episodic and mainly occurring under large swell wave conditions. Coastal protection works now defend much of the coastal edge. This is leading to 'coastal squeeze' where the high water mark is unable to retreat much further landward (resulting in the intertidal zone steepening). North of Carnoustie the rocky foreshore provides additional protection to the coastal edge with erosion appearing to be limited to episodic (storm) events. At Easthaven, erosion is an increasing concern. However, there is anecdotal evidence that the width of the hinterland between the beach and most seaward housing was much less than at present earlier this century (Mitchell, 1997). Nett longshore transport along the coastline to the south of Arbroath does not appear to as great as on other parts of the coastline (although longshore transport in both directions along the coast may be substantial).

Maintenance dredging is conducted at Tayport, Dundee and Arbroath Harbours within sub-cell 2a. The following information is extracted from the UK Dredged Material Database, (MAFF, 1995b), for the period between 1986 and 1993:

Location	**Year**	**Authority**	**Dump Site Name**
Tayport	1989	Tayport Harbour Authority	Firth of Tay
Dundee	Annually	Dundee Port Authority	Various within Firth of Tay
Arbroath	Annually	Arbroath Harbour Authority	Arbroath

At Tayport and Dundee siltation is caused by dominantly silt material transported within the Tay Estuary. At Arbroath a study into the causes of siltation was conducted by HR Wallingford (HR Wallingford, 1969). This identified that the main source of silt for transport into the harbour was from the Brothock Burn and the Lifeboat House Beach. The silt material tended to be suspended by waves and transported by the flood tide into the harbour. It should be noted that dredging of the navigation channel to Perth is also conducted with the spoil dumped in the location of the Tay Bridge.

Summary of erosion and accretion

Widespread erosion is occurring on much of the coastline of North Fife and Angus. At present the most seriously affected areas are the southern coastline of the Eden Estuary, the Monifieth to Barnhill frontage and the Carnoustie frontage. Episodic storm erosion is also occurring along most of the frontage to the south of St Andrews and to the north of Carnoustie. Accretion is occurring along much of Tentsmuir Sands.

5.3.4 Coastal defences

Coastal protection work is largely limited along the north Fife coast to the frontages around St Andrews and the Eden Estuary and is shown in Figure 18. A vertical concrete sea wall of around 1 to 1.5m high backs most of East Sands, with the exception of a small length of vertical sheet steel piling at the central part of the beach. At the southern end of the West Links, various sections of both concrete and stone seawall have been installed. To the west of Out Head, within the Eden Estuary, a large number of *ad hoc* coastal defence works have been constructed in response to erosion along this frontage. Gabions, in the form of both sloping mattress and vertical baskets, make up most of the defence, although sections of groynes, rock rip-rap and concrete wall have also been constructed. In total approximately 1.1km of coastline has been protected. An assessment of the effectiveness of this coastal protection work was conducted in 1994 with recommendations for a future defence strategy, (HR Wallingford, 1994). Much of the Leuchars airbase frontage, on the opposite side of the Eden estuary, is also protected with a variety of designed structures (e.g. revetments and gabion baskets) and more *ad hoc* approaches, such as tipped rubble.

To the west of the castle at Broughty Ferry, the coastline has been developed and is completely man-made. To the east, a variety of coastal defence works occur (Figure 18). At the eastern end of Broughty Ferry, wooden groynes have been installed to control the longshore drift of material. At present these groynes are in good repair and contain a large volume of beach material. Wooden breastworks extends along the crest of these groynes. Older groynes, in a much poorer state of repair control longshore sediment movements along parts of the Barnhill frontage. The effect of these groyne systems is to hold material within the groyne bays and has led to sediment starvation on the adjacent unprotected sections. At Monifieth, a substantial rock revetment now protects much of the frontage affected by erosion of the (now virtually non-existent) dune system.

Much of the sandy beach coastline of Carnoustie Bay is now protected by hard defences following substantial beach and dune erosion. Approximately 2km of rock revetment between Buddon Ness and Barry Burn was constructed in 1992 to protect the dune face on the eastern facing Barry Sands (HR Wallingford 1989, 1991). Along Carnoustie beach, a sloping gabion mattress and rock revetment, both constructed in 1989 by Angus District Council, protect much of the edge of the links along this frontage.

At Arbroath, both the East and West Links are protected by concrete sea walls. At the West Links a number of sea wall types have been built, including a vertical concrete wall, sloping stepped concrete wall with wave return wall and a sloping masonry wall. A vertical concrete wall fronts the East Links.

No information on beach monitoring is available for the coastline of Fife. The main beach areas on the Tayside coastline of this sub-cell are all now monitored regularly. The groyne scheme at Barnhill and beach at Broughty Ferry have been monitored by Dundee District Council since 1989 (now City of Dundee Council). Similarly Angus DC (now Angus Council) have monitored the coastal defences and beach at Carnoustie since 1989. To the north between West Haven and the West Links at Arbroath, and between Barnhill and Monifieth, routine monitoring since 1989 was conducted by Tayside Regional Council. The Property Services Agency has also conducted a number of beach profile surveys along the eastern frontage of Barry Sands. Years of known surveys are given in Figure 18.

5.4 Sub-cell 2b Deil's Head to Milton Ness

5.4.1 Geology

The underlying geology is principally lower Old Red Sandstone, deposited in the Devonian between 408 and 360 million years ago. Outcrops of these sediments occur along the coastline between the Deil's Head and Lang Crag. Outcrops of mainly andesitic and basaltic lavas and tuffs have formed a "hard" cliffed coastline between Lang Crag and the southern end of Lunan Bay and from the northern end of Lunan Bay to Scurry Ness. Much of this "hard" coastline is designated as an SSSI on account of the coastal geology. The northern edge of this second outcrop of igneous rock is bounded by the North Tay Fault which appears at the coastline at Ferrymen. The old cliff line at St Cyrus is of similar igneous nature.

As with much of the coastline of Cell 2, material deposited as the ice sheet retreated at the end of the last ice age has supplied the majority of the beach material in this sub-cell. The Old Red Sandstone cliffs between Arbroath and Lang Crag and the basaltic and sandstone cliffs to the north of Lunan Bay are capped with boulder clay deposits. Fluvio-glacial sands and gravels were deposited by meltwater in Lunan Bay, around Montrose Basin and over much of the adjoining seabed. The reworking of these sand and gravel deposits by river, tidal, wave and wind processes has formed the present day beach and coastal hinterland areas. During early postglacial times, these glacial deposits will have been supplemented by a large volume of river borne sands and gravels (washed out from glacial deposits upstream). However during the postglacial period this supply will have gradually reduced. Such deposits are evident at the mouth of the South Esk, where it passes into Montrose Basin.

The influence of previous and higher relative sea levels is very much in evidence with a distinct fossil cliff and examples of raised beaches backing the beach system at both Lunan Bay and St Cyrus. Around Montrose Basin there is evidence of several raised beaches and at one time the basin would have been twice its present size and open to the sea along much of its eastern flank. The peninsula upon which Montrose now stands is formed upon a shingle bar of rounded pebbles upon which the links have developed. It is uncertain how this shingle bar developed (for example whether it is a bay-bar feature formed when sea levels were falling or whether it was formed during a period when there was a strong southerly longshore transport - or a combination of the two). The basin is designated as an SSSI partly on account of its geomorphological importance. With falling sea levels (around 6000 years BP) a large amount of sand was blown onshore ultimately forming the links area.

5.4.2 Hydraulic processes

The tidal cycle is semi-diurnal and mesotidal in range with both the spring and neap ranges increasing to the south of the sub-cell. At Montrose, the spring tidal range is 4.1m and the neap range 2.0m, Figure 11 and Table 13. To the south of the sub-cell, at Arbroath, the spring range is 4.3m and corresponding neap range is 2.3m. The tidal current flows are nearly rectilinear with the flood tide flowing in a southerly direction along the coast and the ebb tide flowing to the north. A clockwise changeover of flood and ebb tides occurs. Tidal current flows are of similar magnitude on both the flood and ebb tides with peak current speeds of about 1.3knots (0.65ms^{-1}) occurring off Scurdie Ness. A high tide the mean spring velocity is approximately 0.55ms^{-1} flowing to the south across the mouth of Lunan Bay.

Tidal flows at the entrance to Montrose Basin can be extremely strong with a spring rate of up to 7knots (3.5ms^{-1}). Under such conditions there is an area of turbulence off the entrance during the out-going stream. Such strong tidal action has a significant effect on the littoral processes at the southern end of the beach, forming the Annat Bank and possibly recirculating material back onto the beach further north.

Table 13 Sub-cell 2b - Predicted tidal levels and ranges

Sub-cell	Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	ODN to CD (m)
2a	Arbroath	2.2	-2.1	4.3	1.3	-1.0	2.3	+2.80
2b	Montrose	2.15	-1.95	4.1	1.25	-0.75	2.0	+2.65

In Table 13 the tidal elevations are quoted relative to Ordnance Datum Newlyn (the standard land based datum). The conversion to the local Chart Datum (where known) is shown in the final column.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. Within these studies there are no locations in sub-cell 2b where extreme water level predictions were made.

The latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest and also include allowances for trends in mean sea level rise (and hence have not been reproduced in this report). This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

The offshore total and swell wave climate for the region to the east of the mouth of the River Tay is shown in Figures 12 and 13 respectively. The dominant wave conditions approach from between 20°N and 60°N with, on average, approximately 35% of the conditions occurring from this sector. Extreme wave conditions (greater than 4m) can be experienced from all of the easterly sector. Extreme wave conditions have been predicted from the Met Office Wave Model and are detailed in Table 11 in Section 5.3.2.

Swell waves contribute a significant proportion of the total wave energy experienced in this region. The largest percentage of this swell will have been generated within the Norwegian Sea, with some heavily diffracted swell from the North Atlantic also contributing. Due to the restricted fetch lengths to the south east, little swell is experienced from this sector. Extreme swell wave heights for this offshore region are detailed in Table 12 in Section 5.3.2.

An assessment of wave conditions closer to the shoreline, albeit still in deep water, (HR Wallingford, 1993b) has shown that, due to the orientation of the coastline, waves from between 20°N and 60°N have less influence at the coastline.

5.4.3 Littoral processes

The main beach areas within this sub-cell are dominantly sand, backed by dunes and links areas, (Figure 19). Material deposited at the end of the last ice age has been the dominant source of material for the formation of the 'soft' areas of coastline. Much of this material is at present "stored" in the hinterland, particularly at Montrose and reworking of these deposits is relatively low. The input of beach material from other sources is also low (Figure 20). The intertidal basin at Montrose acts as a filter to material transported down the River South Esk with the basin slowly accreting. Some material will be transported into the coastal regime due to the action of tidal flushing of the basin, but the volume of material will be low and confined to very fine material which will probably be transported offshore. Other fluvial input from the River North Esk or the Lunan Water will be insignificant. Similarly the input of material from cliff erosion is very small and there is unlikely to be any long term nett accumulation of material from offshore.

The sandstone cliffs between Arbroath and Lunan Bay form an effective boundary blocking any appreciable exchange of beach sediment from the beaches to the south of Arbroath and those to the north, Figure 20. Within the sub-cell, both Lunan Bay and the Montrose to St Cyrus system can be considered as self-contained units. At Lunan Bay the beach appears to be in a state of dynamic equilibrium with little apparent nett longshore transport. The headlands, bounding the beach at either end, will provide a sheltering effect restricting waves reaching the shore at a wide angle of incidence and hence reducing the potential for longshore transport in either direction. In general terms this has produced a relatively stable bay planshape. Despite this, erosion is presently occurring with bombs associated with the second World War (which had been buried in the dunes) recently uncovered. Wave action will also result in a cyclic onshore/offshore movement of beach due to seasonal changes in the wave climate with lowering of the upper beach levels and undercutting of the frontal dune face occurring under storm conditions. Under more constructive wave conditions material will be transported back up the beach, with wind action transferring material to the frontal dunes. The main erosive influences at Lunan Bay are linked to human activities with erosion of the dunes occurring to the north of the Lunan Water where pedestrians gain access to the beach from the car park. This erosion is further intensified by wind action.

At Montrose, the system is somewhat different. Nett drift is presently to the north due to the dominance of waves from the south east quadrant. At the southern end of the beach, the present wave induced drift rate can be considered relatively high. The present northward drift may also account for the anecdotal evidence that the Annat Bank appears to be lowering. This rate gradually reduces to the north to St Cyrus due to the changing orientation of the coastline. Tidal currents are also likely to be responsible for the movement of beach material. Although these currents will not be of sufficient magnitude to suspend and transport a high volume of material, the stirring action of breaking waves will allow material to be brought into suspension which can then be moved by such currents. Peak current speeds on both the flood and ebb tides are similar in magnitude. However, at high tide the currents flow strongly in a southerly direction and are capable of transporting beach material on the lower sections of the intertidal beach. This process can explain the periodic siltation of the dredged channel leading to Montrose Harbour. At the southern end of the beach at Montrose substantial erosion of both the beach and frontal dunes is occurring due to the nett movement of material to the north. Beach levels in front of the seawall had fallen to a dangerous level and substantial erosion of the dune face further north is now affecting a number of the tees at the golf course. At present this erosion is about 100,000m^3/year at The Faulds, (HR Wallingford, 1993b). Historical map analysis of the frontage at Montrose has been conducted using maps between 1863 and 1964 (HR Wallingford, 1993b). This showed little change in the position of Mean High and Mean Low water over this period. Indeed if anything, there had been a slight advance of the high water line at The Faulds during this period, although the intertidal zone has narrowed with the Low Water mark receding shorewards. It is suspected that this recent increase in erosion can be attributed to a change in the wind conditions, and hence wave climate, over the last six or seven years. At present it is too early to ascertain whether this change in the wind and wave climate will continue.

To the north of the River North Esk, the eroding coastline changes into an accreting coastline with sand accumulating along the frontage at St Cyrus. The abundance of sand on this beach protects the coastal edge with little evidence of any erosion of the dune face even under storm conditions. A complex series of intertidal ridges and runnels is evident, particularly during summer months.

Maintenance dredging to maintain a depth of -5.5m CD in the approach channel to Montrose Port is normally carried out annually. Dredging records are available from the Harbour Master at Montrose since around 1984. At present dredged material is deposited in a spoil area 2.5km south east of Boddin Point. This represents a nett loss of sand from the Scurdie Ness to Milton Ness frontage. However, dredging of the approach channel is unlikely to be a significant factor in the erosion experienced along the coastline to the north of the sea wall at Montrose (HR Wallingford, 1993b).

Summary of erosion and accretion

The Montrose frontage is experiencing significant erosion at present with large volumes of beach and dune material being transported to the north of the beach unit resulting in accretion occurring at St Cyrus. Present day erosion of the frontal dunes at Lunan Bay is occurring but the magnitude is much less than that at Montrose.

5.4.4 Coastal defences

Coastal protection work within this sub-cell is concentrated at the southern end of the beach at Montrose, Figure 21. A sheet pile wall capped by a sloping concrete revetment was constructed to protect the car park in 1954. More recently rock has been placed to protect the dune face to the south of the sea wall. This protection now extends from the sea wall to the Glaxo factory. Gabions were originally used to protect the dune edge fronting the factory and have subsequently been replaced by a rock revetment. Beach drawdown in front of the sea wall has resulted in rock toe protection being placed at the toe of the sheet piling. Originally this was placed to the south of the access steps, but this was extended along the entire sea wall frontage in 1994 after beach levels fronting the seawall dropped to a dangerous level. Associated with this work, beach material was placed in front of the sea wall and a short rock groyne constructed at the northern end of the sea wall.

Three short stretches of rock breakwater have recently being completed along the golf club frontage to reduce the rate of frontal dune erosion at the most critical locations, in this case three of the golf club tees. These structures have been designed only to protect these locations, i.e. the unprotected frontal dunes will continue to erode, and to have minimal impact on the littoral processes (both cross-shore and longshore) occurring on the intertidal beach. A further study of the frontage is presently (1998) being conducted for Angus Council by Halcrows.

The areas of the coastline monitored are indicated in Figure 21. The former Tayside Regional Council conducted beach surveys along the beach frontage at Lunan Bay from 1989 until local government reorganisation in 1996. Similarly the former Angus District Council and the present Angus Council have conducted beach profile surveys, at approximately six month intervals since 1989, at ten locations on the southern beach at Montrose.

5.5 Sub-cell 2c Milton Ness to Girdle Ness

5.5.1 Geology

The coastline of this sub-cell stretching from Milton Ness in the south to Girdle Ness in the north is dominated by the underlying hard geology. To the south of the Highland Boundary Fault, which appears on the coastline at Stonehaven, the bedrock consists of Old Red Sandstone deposits laid down around 400 Ma. To the south of Inverbervie, this rock is typically exposed in the form of a low abrasion platform. North of Inverbervie, Old Red Sandstone cliffs increase in elevation. At a number of locations, for instance Crawton Bay, outcrops of conglomerate and igneous rock are interbedded within these cliffs. At Stonehaven, adjacent to the Fault, Ordovician lavas, shales and cherts of the Highland Border complex outcrop.

To the north of the Highland Boundary Fault, the bedrock consists of much older metamorphic rock of Dalradian age (formed more than 600 Ma). Quartzite and schistose grits from the later part of the Dalradian sequence occur immediately to the north of the Highland Boundary Fault, with schists of slightly older age to the north of Cove Bay. An intrusive outcrop of granite is present to the south of Cove Bay. At Nigg Bay the elevation of the bed rock decreases towards the centre of the bay before rising to Girdle Ness. Five SSSIs are designated along this coastline, three of which are due, entirely or in part to their geological importance (Appendix 1).

Glacial till deposits of varying thickness cap the underlying rocks, Figure 10. To the south of Inverbervie such deposits are typically thin with the coastal edge at a relatively low elevation. To the north of Stonehaven such till deposits can be up to 35m thick resting on the bedrock cliffs. Small fluvio-glacial deposits of sand and shingle back the bays at Inverbervie and Stonehaven. Raised beaches and stretches of fossil cliffs characterise the coastal hinterland between Milton Ness and Inverbervie with Milton Ness being designated an SSSI on account of well preserved evidence of previous sea level changes. Fluvio-glacial deposits also overlie Girdle Ness. Postglacial alluvium deposits occur along the valley which backs Nigg Bay; it is considered that this was once a previous course of the Dee. The glacial deposits backing Nigg Bay have been designated SSSI status.

5.5.2 Hydraulic processes

The spring and neap tidal ranges for this sub-cell are shown in Figure 11 and detailed in Table 14. No recording tidal gauges are located within this stretch of coastline although an A-class tidal gauge is situated at the northern boundary at Aberdeen Harbour, with a tidal gauge also located at Montrose. Tidal levels are given for Stonehaven on the Admiralty Charts. Tidal flows are rectilinear with the flood tide running parallel with the coastline in a southerly direction and ebb tide to the north. High water takes approximately 1 hour to travel along the length of the sub-cell. Tidal currents are of similar magnitude to other parts of the eastern coastline. An Admiralty Diamond 11km east of Stonehaven gives a peak Spring tidal current of 1.4 knots, ($0.7 ms^{-1}$) and peak neap current of 0.7 knots, ($0.35 ms^{-1}$). At high tide the current flows in a southerly direction with a Mean spring rate of about $0.6 ms^{-1}$. Current velocities closer into the shoreline are likely to be weaker, for instance the peak spring tidal current just offshore of Stonehaven Bay is around 1 knot, ($0.5 ms^{-1}$).

Table 14 Sub-cell 2c - Predicted tidal levels and ranges

Sub-cell	Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	ODN to CD (m)
2b	Montrose	2.15	-1.95	4.10	1.25	-0.75	2.0	+2.65
2c	Stonehaven	2.05	-1.85	4.00	1.15	-0.75	1.90	+2.45
2d	ABERDEEN	2.05	-1.65	3.70	1.15	-0.65	1.80	+2.25

In Table 14 the tidal elevations are quoted relative to Ordnance Datum Newlyn (the standard land based datum). The conversion to the local Chart Datum (where known) is shown in the final column.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications there are no locations where predictions have been made, the closest being Aberdeen.

The latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water level predictions depend upon the year of interest, allowing for trends in mean sea level rise, and hence have not been reproduced within this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

The offshore total and swell wave climate, derived from the Met Office Wave Model Archives, for the region to the east of Sub-cell 2c is shown in Figures 14 and 15 respectively. The directional frequency of wave conditions is fairly evenly spread from all direction sectors between 0°N and 200°N with a slight bias from between 0°N and 60°N due to the dominance of swell conditions from this sector. Extreme wave conditions can be experienced from almost any directional sector between 0°N and 200°N. Extreme wave conditions have been predicted from the Met Office Wave Model and are detailed in the table below:

Table 15 Total sea extreme significant wave heights

Return Period (Years)	Significant wave height (m)
1	6.36
10	7.69
100	8.95

Swell waves contribute a significant proportion of the total wave energy experienced in this region. The largest percentage of this swell will have been generated within the Norwegian Sea, with some heavily diffracted swell from the North Atlantic also contributing. Due to the restricted fetch lengths to the east and south, little swell is experienced from this sector. Extreme swell wave heights for this offshore region are detailed in Table 16.

Table 16 Swell wave extreme significant wave heights

Return Period (Years)	Significant wave height (m)
1	3.71
10	4.66
100	5.56

The nearshore bathymetry within this cell is variable and the coastline highly indented. Hence, wave conditions experienced at the coastline are highly variable and dependent on the offshore bathymetry, orientation of the coastline and the degree of shelter provided by rock headlands or wave cut platforms. The few beach areas within this cell are pocket or bayhead type beaches often bounded by headlands or rock abrasion platforms. These beach areas are directly exposed to wave conditions from a narrow wave window. However, waves from a much wider offshore directional sector will be experienced due to refraction and strong diffraction processes around the headlands.

5.5.3 Littoral processes

The volume of beach material within this sub-cell is limited and generally consists of poorly sorted shingle which overlies bedrock, Figure 19. Between Tangleha and Gourdon a shingle storm beach overlies the rock abrasion platform. Under more commonly occurring wave conditions this shingle will be relatively inactive. Only under storm conditions will it become active. On such beaches there will be little significant longshore drift, most of the changes will occur in the cross-shore direction (Figure 20).

The main beach areas at Inverbervie, Stonehaven and Nigg Bay have resulted from the reworking of mainly fluvio-glacial deposits. These superficial deposits are now protected from erosion by coastal protection works. Hence the amount of new material presently being made available from coastal erosion is low. Erosion of less resilient cliffs provides a small input of beach material to the many pocket beaches. Spate flows down the Cowie Water will bring a limited amount of shingle onto the beach.

Sediment losses from the characteristic pocket beaches occurring between Inverbervie and Nigg Bay will be dominated by losses offshore. All of these beach units are constrained by either rock headlands or abrasion platforms which restrict longshore sediment transport processes. Given that there is at present a very low input of beach material, and that beach volumes are not decreasing at any great rate, it is assumed that offshore losses will be of a similar magnitude (or marginally greater) than the present sediment input.

The shingle ridge at Inverbervie appears to be relatively stable, with no long term nett erosion or accretion, although the beach profile will change under storm wave conditions. Waves are restricted from reaching the coastline at any great angle due to the rock platforms at either end of the bay, so the potential for longshore transport is greatly reduced. At Stonehaven the dominant process appears to be a cross-shore movement of shingle with the elevation of the beach at the sea wall varying depending on the wave climate. There would also appear to be nett movement of beach material to the south resulting in a reduced volume of beach material at the northern end. The existence of the sand beach at the southern end can be partly attributed to the winnowing of sand sized material from the beach further north which is then moved southwards under north easterly wave conditions. This beach will also receive an input of sand material from the Carron Water, although this rate will be low. Transport of material to the north, during storms from the south easterly quadrant, will be constrained by the training wall of the Cowie Water which will act as a groyne blocking the transport of material on the upper beach to the north.

The beach at Nigg Bay appears to be relatively stable. Offshore rock reefs will protect the beach from severe wave attack. Overwashing of the back of the beach will occur under high tide conditions coupled with severe wave conditions.

The MAFF dredging licence database (1995b) indicates that maintenance dredging was conducted at Stonehaven in 1987. There is no information on the source of the siltation but the dredging volumes are low.

<u>Summary of erosion and accretion</u>
There are no locations where significant long term erosion or accretion are occurring within this sub-cell. Most erosion occurring will be episodic, limited to storm events.

5.5.4 Coastal defences

Coastal protection work is relatively limited along this coastline, with the only major scheme found at Stonehaven. Other small schemes have been completed in response to localised problems and in general, due to the lack of beach sediments, have little detrimental influence. Details of the coastal protection schemes present within this sub-cell are given in Figure 21.

At both Tangleha and Johnshaven gabions have been installed. Further north at Gourdon a small stretch of rock armour has been placed and a masonry wall protects much of the frontage to the south of the harbour.

Backing the shingle ridge along the central part of the bay at Inverbervie is a low concrete block sloping revetment. A relatively healthy shingle beach fronts the revetment with there being little evidence of any wave damage. At the northern end of the revetment, a building located directly behind the beach is protected by a gabion wall which extends into the shingle beach. This structure has been constructed relatively recently and as yet displays little sign of wave damage. However, given the seaward location of the front face of the gabions it is expected that storm wave conditions will damage this structure in due course.

A rock revetment, directly to the south of Stonehaven harbour, has recently been constructed to protect a small area of land upon which some huts are situated. The rock used to construct the revetment is extremely variable in size, i.e. smaller rocks fill the voids created by the larger rock. This will decrease the hydraulic efficiency of the structure resulting in a greater percentage of wave energy being reflected off it. This in turn could increase wave activity in the region of the harbour entrance.

To the north of the harbour at Stonehaven, a rock revetment, constructed on top of a rock abrasion platform, protects a car park. Further around the bay, a low vertical sea wall extends for around 150m to the south of Cowie Water. Although a shingle upper beach fronts this wall, it is likely that wave overtopping will occur under storm conditions. To the north of Cowie Water, the entire beach frontage has been protected. A stepped concrete sea wall with wave return wall occurs for around 400m immediately to the north of the Cowie Water. Wave overtopping of this defence is a problem. Beyond this, a low vertical sea wall protects the coastal edge to the village of Cowie. The hard defences backing the beach at Stonehaven affect beach levels due to a high percentage of incident wave energy being reflected from these structures (hence resulting in a seaward movement of beach material). This could become increasingly significant under a scenario of climatic change (Chapter 6).

Short stretches of concrete sea walls are found at Cove and protecting the road at the northern end of Nigg Bay. These have little impact on the beach regime.

Monitoring of the coastline has been conducted by the former Grampian Regional Council at three locations, Tangleha, Stonehaven and Nigg Bay, Figure 21. Beach levels have also been recorded at Stonehaven. No information on the frequency or length of record is available. It is not known whether the new Unitary Authorities are continuing this monitoring.

5.6 Sub-cell 2d Girdle Ness to Cairnbulg Point

5.6.1 Geology

The hard geology of this sub-cell is only significantly exposed between Collieston and Peterhead and in a number of small intertidal outcrops north of Peterhead. Metamorphic rocks of Dalradian age (> 600 Ma) underlie much of this sub-cell. The cliffed coastline between Collieston and south Cruden Bay is mainly composed of quartzites and schists which are resilient to marine erosion. North of Cruden Bay these give way to cliffs of granite which extend from Port Errol to Peterhead. Within these cliffs dolerite dykes occur which are more easily eroded by marine action than the granite, giving rise to inlets, stacks and geos.

Fluvio-glacial sands and gravels deposited as the most recent ice sheet retreated overlie the bedrock between the River Dee and Balmedie and to the north of Scotstown Head. Overlying much of these are extensive postglacial deposits of blown sand which form the links and dune areas along the coastline between the River Dee and Collieston and between Peterhead and Inverallochy. A thin layer of boulder clay occurs to the north of Collieston with morainic drift, which is of finer material than the boulder clay, capping much of the cliffed coastline. These deposits are little affected by marine processes.

Evidence of formerly higher relative sea levels back much of the "soft" beach coastline within this sub-cell. The hinterland around Rattray Head has a particularly wide range of fossil and active geomorphological features and is, in consequence, designated as an SSSI.

5.6.2 Hydraulic processes

The spring and neap tidal ranges for this sub-cell are detailed in Table 17 and shown in Figure 11. An A-class tide recording gauge is located at Aberdeen Harbour with gauges (which are not part of the A-class network) also located at Peterhead and Fraserburgh.

Table 17 Sub-cell 2d - Predicted tidal levels and ranges

Sub-cell	Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	ODN to CD (m)
2d	ABERDEEN	2.05	-1.65	3.70	1.15	-0.65	1.80	+2.25
2d	Peterhead	1.60	-1.70	3.30	0.9	-0.70	1.60	+2.20
3	Fraserburgh	1.70	-1.60	3.30	0.9	-0.70	1.60	+2.20

In Table 17 the tidal elevations are quoted relative to Ordnance Datum Newlyn (the standard land based datum). The conversion to the local Chart Datum (where known) is shown in the final column.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications the only location in sub-cell 2d where predictions of extreme water levels have been made is Aberdeen. The predictions are detailed in the Table 18.

Table 18 Extreme water level predictions at Aberdeen

Graff (1981):

Location	Return period levels (height above ODN (m))						
	1	5	10	20	50	100	250
Aberdeen	2.64	2.81	2.88	2.96	3.03	3.08	3.13

Coles & Tawn (1990):

Location	Probability of annual maximum tidal levels (m ODN)		
	10%	1%	0.1%
Aberdeen	2.88	3.07	3.22

The latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest allowing for trends in mean sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Flooding at times of extreme high tides, coupled with high river flows, affects parts of Riverside Drive and a number of properties backing this on the northern bank of the Dee in Aberdeen. Other than this, coastal inundation affecting infrastructure or buildings is limited. High tidal conditions may affect properties situated along the north bank of the Water of Cruden at Port Errol. Similarly, high tides in conjunction with large wave conditions will cause overtopping of the shingle beach and affect properties along the coastal edge at Inverallochy.

The flood tidal flow follows the coastline from the Moray Firth around Cairnbulg Point. This meets a southerly flowing stream from offshore. The resulting flood tide runs parallel to the coastline. The flood and ebb tide is strongly rectilinear with the ebb tide flowing in the opposite northerly direction along the coast. Tidal currents are relatively strong at the northern end of this coastline, decreasing slightly to the south. Approximately 5 miles offshore, peak spring tidal current speeds can exceed 2 knots ($1ms^{-1}$) along much of the coastline, with peak neap currents of up to 1.2 knots ($0.6ms^{-1}$). Although these current speeds will reduce closer to the shoreline, strong currents can be expected around headlands such as Girdle Ness. Analysis of Admiralty diamonds shows strong currents (up to $0.85ms^{-1}$ off Peterhead) flowing to the south at high tide. Current speeds will not be as strong closer into the coastline but will still be sufficient to transport material on the intertidal beach to the south.

Between Aberdeen and Peterhead there is unlikely to be any great variation in the wave climate along the coastline. The total sea and swell wave climates offshore of Aberdeen are shown in Figures 14 and 15 with extreme conditions detailed in Tables 15 and 16. The offshore climate experiences waves from all direction sectors between 0°N and 200°N with a slight bias from between 0°N and 60°N due to the dominance of swell conditions (generated in the Norwegian Sea) from this sector.

Numerical modelling of the wave climate offshore of Aberdeen Harbour, (HR Wallingford, 1988a) indicates that the coastline is dominantly affected by waves from between 30°N through to 180°N. The prevailing wave direction is from the south and south east. Storm wave conditions can be experienced from any direction between about 30°N to 150°N, with the most common direction for such conditions being between east and south east. The coastline to the north of Peterhead is more exposed to waves from the north and north east, with the headland at Peterhead providing some shelter from waves from a more southerly direction.

5.6.3 Littoral processes

The extensive fluvio- and postglacial deposits of this coastline have been reworked as sea level has fluctuated to form many of the features evident today within the coastal zone. There is still a high potential input of beach material from these sources. However, given that sea levels are at present relatively stable there is little fresh active input into the coastal system. As in most of the other sub-cells on the east coast, present day fluvial input is low and will not contribute any significant quantities of beach material. The granite cliffs to the south of Peterhead are extremely resilient to marine erosion and provide little input of beach material, Figures 22 and 23.

Longshore transport of sediment within this sub-cell is dominated by wave action but tidal currents, particularly at high tide, may also transport sediment. The dominant littoral processes are shown in Figure 23. The only detailed study to investigate longshore transport rates and directions was conducted at Aberdeen beach in connection with infilling of the dredged channel at Aberdeen Harbour, (HR Wallingford, 1988a & b). This identified a strong wave induced net transport of sediment from south to north. Siltation of the dredged channel was found to be caused by two factors. Firstly waves from the north and east move some sediment to the south. It appears that there is also a movement of material on the lower beach to the south due to tidal current action. Although such currents will not be of sufficient magnitude to suspend sediment, the stirring action of waves, from any direction, will allow suspension of material which can then be transported by such currents. Along Aberdeen beach there has been a history of erosional problems, (Pallett, 1963; Buchan, 1976; Mather et al, 1978) resulting in various forms of coastal protection work since the late 19th century. Such erosion can be attributed to the nett northward drift of material and the lack of input to the beach system from other sources, i.e. from the River Don or from offshore. The construction of hard defences has cut off the input of material from the eroding coastal edge. Buchan (1976) presented details of nett retreat of both the HWM and LWM at Aberdeen beach since the mid-19th century. The intertidal beach appears to be steepening, with the LWM migrating onshore at a faster rate than that of the HWM. Retreat of the HWM has been restricted by coastal defence work resulting in 'coastal squeeze' and narrower foreshore width. The beach appears to be relatively stable at present, apart from seasonal cyclic changes in level, with an adequate volume of beach material within the groyne bays. Littoral processes at the mouth of the River Don are complex. At present erosion is occurring to the north of the river outlet.

A nett northerly drift of material occurs along the entire frontage between the River Dee and the Sands of Forvie. This rate decreases to the north as the orientation of the coastline changes. At the mouths of the Rivers Don and Ythan there is a complex interchange of sediment due to the action of river flows, tidal currents and waves. To the north of the River Don the beach is in a relatively natural state. Complex dynamic features such as ridge and runnel formations are common, particularly during the summer period, with rip currents also a common feature of this coastline. Localised areas of erosion and accretion do occur and can vary over time. The erosion/accretion process is dominantly cyclic with the coastline responding to the seasonal change in the wave climate. Beach levels tend to be drawn down, with wave undercutting of the frontal dunes, during winter months, with an onshore movement of sand and accretion of the dune face during summer periods. As at the mouth of the Don, complex coastal processes result in a dynamic erosion/accretion pattern within and around the Ythan estuary. Anthropogenic activities have resulted in severe erosion of parts of the dune system. MoD use, dumping and recreational activities have all contributed to substantial dune deflation and blowout activity. For instance large blowout features have occurred at Balmedie due to pedestrian access to the beach from the car park, despite the provision of boardwalks. Extensive areas of deflation have formed in parts of the dune zone, e.g. just to the north of the car park at Balmedie. Wind action is also promoting accretion of sand, mainly in the frontal dunes, at various locations.

At Cruden Bay there is little evidence of significant present day nett longshore drift. Although material will be transported longshore, this can occur in either direction. The dominant sediment transport mechanism appears to be a healthy onshore/offshore regime controlled by the wave climate. Some erosion due to pedestrian trampling is evident at the access point of the beach at the north end. Some wind erosion is also evident at the centre of the bay where a stream cuts through the dunes.

North of Peterhead, there is less evidence of nett longshore drift than at the beaches around Aberdeen. The pattern of the build up of salients at such places as Rattray and Scotstown Heads indicates a relatively stable regime, at present, in terms of nett drift. Drift rates will depend very heavily on the wave conditions, though tidal currents acting in conjunction with waves are also likely to be capable of moving sediment. Cyclic seasonal effects of frontal dune undercutting and beach lowering under storm wave conditions and re-accretion due to swell wave and wind action are evident along the entire coastline. Where access can be gained to the coastline, anthropogenic influences such as off-road motor cycles and pedestrian access, are having a detrimental effect on the stability of the dune system, for instance at Scotstown and Rattray Head. To the north of St Combs, the coastal edge is undercutting with a 2m high sand cliff formed over a considerable length of frontage. Part of this has been protected by rock rip-rap.

Maintenance dredging is routinely conducted (at least yearly) at Aberdeen and Peterhead. Significant capital dredging, associated with the port development, has also been conducted at Peterhead. At Aberdeen beach material moved in a southerly direction along the lower part of the beach, dominantly by tidal currents, is responsible for the siltation. Analysis of dredging rates was conducted by HR Wallingford (1988a &b).

<u>Summary of erosion and accretion</u>
The beach along the Aberdeen frontage is suffering from long term erosion as is most of the Balmedie frontage further north. Accretion is presently occurring along the Newburgh frontage and Sands of Forvie. To the north of Peterhead erosion of the frontal dunes is generally caused by episodic storm events rather than long term processes.

5.6.4 Coastal defences

A summary and details of the various coastal protection work within this sub-cell are presented in Figure 24. The main coastal protection work is at Aberdeen beach, where a sea wall consisting of sloping precast concrete units resting on steel sheet piles backs the beach for much of the frontage between the Rivers Dee and Don. Associated with this construction, timber groynes to control the longshore drift rate were also installed. To the south of the sea wall, at Footdee, a rock revetment has been constructed and is presently in good condition. Between the north end of the sea wall and the mouth of the River Don, a sloping gabion mattress protects the dune face for around 210m. This is in an extremely poor state of repair.

At Collieston, a masonry wall approximately 75m in length protects the shoreline to the south west of the harbour. This is in relatively good condition but has required periodic repair. A similar masonry wall is present at Port Errol, at the northern end of Cruden Bay. This is in a very poor condition (1995).

Peterhead harbour is protected by a number of concrete and rock breakwaters. Within Peterhead Bay, a rock revetment has been constructed, relatively recently, protecting an area of reclaimed land at Kirktown. The main coastal protection work is a sea wall which extends from the harbour to the George Birnie Memorial Bridge. Two types of wall exist. Fronting the Roanhead area of Peterhead is a vertical masonry wall. Further west at Buchanhaven, the wall has been upgraded during the early 1980s and is now concrete. North of Peterhead, there are few coastal protection works. A small length of rock rip-rap protects the eroding dune edge at the northern end of the village of St Combs. Due to the steep slope of this rip rap and the size of the rock, this defence is unlikely to withstand severe wave attack. At Inverallochy a sloping concrete block revetment backs the thin shingle beach along the southern part of the village. The revetment is relatively low and it is likely that overtopping of the structure will be a common occurrence during high tidal level events.

5.7 Summary of effects of coastal processes on natural and cultural heritage sites

5.7.1 Introduction

The natural and cultural heritage of the coastline of Scotland is rich and diverse. Much of the character and many of the features of natural heritage interest are due to the effects of the last Ice Age and subsequent postglacial climatic variations. It is since the last Ice Age that evidence of the first inhabitants of Scotland can be traced. Effects of coastal processes have been instrumental in developing both the natural and cultural heritage around the coast. For instance many important coastal geomorphological features are due to processes acting at previously much higher sea levels. Archaeological sites also demonstrate changes in these processes over the last 10,000 years or so. For example Skara Brae in Orkney, now requiring engineering protection from the sea, was once some considerable distance from the shoreline. Remains in Gleann Sheillach south of Oban indicate that 6,000 years ago this site was at the head of a sea loch even though now it is 1.5km from the shoreline (Ashmore, 1994).

The present threat of erosion and the likelihood of future climatic changes considerably increases the risks of many of these sites being affected by erosion and/or flooding. However, as discussed in the next chapter, our present knowledge of either the patterns of future climatic change or how the coastline will respond to these changes is extremely limited. It is impossible at present to predict with any confidence what changes will occur in the coastline for example in the next one hundred years or indeed in the next ten years. However, the next sections attempt to present a broad based summary of the influences of present day and possible future coastal processes upon natural and culturally designated areas. **This report is concerned with the macro-scale processes occurring around the coastline. To generalise about the effects of coastal processes, particularly on**

individual cultural heritage sites, is extremely difficult, and many such sites require much more detailed, individual assessments to establish and prioritise the particular potential risks.

5.7.2 Natural heritage sites

Figure 7 shows the location of coastal SSSIs within Cell 2, with a summary of their main characteristics provided in Appendix 1. There are 30 Sites of Special Scientific Interest within Cell 2 many of which have been designated on account of geological or geomorphological features.

Present day influences of coastal processes on SSSIs designated because of the solid geology are unlikely to have any great detrimental effect. Many of the designations are due to igneous outcrops, such as volcanic vents, which by their very nature are extremely resilient to marine erosion. The largest impacts of marine erosion on such sites will be where generally younger, less resilient rocks occur such as the Calciferous Sandstone outcrops along the north Fife coast and the Old Red Sandstones to the north of Arbroath (Whiting Ness to Ethie Haven SSSI). However, the overall rate of attrition will still be low due to the protection provided by the shore platform. Further north, particularly to the north of the Highland Boundary Fault, the basement rocks are extremely resilient to marine erosion.

Many of the SSSIs in this cell are designated entirely or in part for the safeguard of 'soft' coastal habitats, such as sand dunes, saltmarsh and tidal flats, and/or for the coastal landforms they contain and processes they demonstrate (as for example the dune systems at Strathbeg, Forvie, Barry Buddon and Tentsmuir).

The maintenance of existing coastal processes of sediment transport, erosion and deposition is crucial for the continued integrity and 'health' of such systems, particularly in respect to those sites specified above designated specifically on account of their geomorphological interest. By their nature, such sites are also those most likely to alter as a consequence of any change in coastal processes resulting from human intervention or climate change. Dune systems presently accumulating sediment, such as at Tentsmuir and St Cyrus, should be less severely impacted by reductions in sediment supply than most others in this cell which lack significant sediment inputs and where erosion may be exacerbated as a result.

At Barry Buddon, much of the eastern flank has been protected, limiting wave erosion. Although much of Barry Links is designated on account of the features within the hinterland, the effects of the MoD defences may be more damaging to the site's interest than any change due to erosion and sediment transport which would have resulted were these not to have been constructed.

The greatest effect of changes in coastal processes on geomorphologically designated SSSIs is likely to occur along the open exposed coastlines to the north of Aberdeen, such as Foveran Links, Sands of Forvie and the Loch of Strathbeg SSSIs. Wave erosion of the frontal dunes is at present causing significant concern at these sites and under an assumed increase in either sea levels, or any increase in the severity or frequency of storms, the situation is unlikely to improve. Most of these systems are in a relatively natural state with minimal human interference and erosion of the frontal dunes is a natural mechanism which increases the volume of sediment within the natural beach defence system in response to either changes in the hydraulic climate or sediment losses from the beach. Some of the important geomorphological features in the immediate hinterland may well be lost to the sea in the medium term future but to try to protect these features, for instance with coastal protection works, may well have a much greater detrimental effect on the adjacent coastline and the designated interests.

Montrose Basin is also an accretionary system which, in this case, is gradually silting up. Wave action from the North Sea does not penetrate into basin. Despite some movement of the main channels, probably linked to varying river flows, it is unlikely that there are going to be any significant natural changes in the overall regime even under the low rates of sea level rise predicted in the near future. Similarly at St Cyrus there is an abundance of sand which protects the frontal dunes from all but the most severe wave conditions and it is unlikely that in the medium term the geomorphological features evident in the hinterland will be significantly influenced by coastal processes.

There are a number of other sites where changes in coastal processes may well have a detrimental effect. For instance small areas of saltmarsh occur on top of the wave cut platform within the Rickle Craig to Scurdie Ness SSSI. Saltmarsh is extremely sensitive to wave erosion and despite the protection afforded by the rock platform, if wave erosion of this marsh does occur then it is likely to be lost. Similar saltmarsh is found within the Fife Ness Coast SSSI.

5.7.3 Cultural heritage sites

The density of archaeological sites from the NMRS database is shown in Figure 9 and in Appendix 2. There appears to be a much lower density of such sites in Cell 2, when compared to the coastline of the Firth of Forth. Whether this is because the coastline of Cell 2 is less developed or because there has been insufficient survey work conducted to locate such sites is not known. No specific surveys appear to have been conducted to locate sites of archaeological importance within the coastal hinterland and to establish the risk to these sites from coastal erosion.

On the Fife and Angus coastlines, many of the recorded sites appear to occur along sections of the coastline fronted by the basement rocks. Although this rock is dominantly of Old Red Sandstone and is susceptible to wave erosion, most of these sites are situated back from the coastal edge and so are relatively safe in the medium term future. Possibly the most important sites at risk along the southern coast of Cell 2 are those around St Andrews where features such as the cathedral are protected by defences in a generally poor state of repair.

At present the most rapidly eroding coastline in Angus is that at Montrose. There appears to be little known evidence of archaeological sites in the immediate hinterland along the most seriously eroded section of coast. A number of sites are noted around the mouth of the North Esk and St Cyrus but this area is presently accreting with a low risk of any present day long term erosion. To the north of St Cyrus, the almost continuous rock platform affords some protection to the coastal edge and raised beaches which back the shoreline, but some coastal edge retreat will be experienced under storm conditions.

The frontage of most concern, in terms of the threat to archaeological sites within Cell 2, is probably that to the north of Aberdeen between the Bridge of Don and the Sands of Forvie and again to the north of Peterhead. Both these coastlines are experiencing considerable landward retreat of the frontal dunes due to wave erosion which will continue if similar patterns to those experienced on the east coast of Scotland in the last few years continue. Along such coastlines, erosion is likely to proceed at a greater rate along the central sections of the bay features than behind the rock outcrops such as at Rattray and Scotstown Heads. Despite the most severe threat being that of wave erosion, where anthropogenic activities have denuded the dune systems of vegetation, such as around Balmedie, there is considerable potential for wind erosion to either uncover new sites or submerge existing ones.

6 Climate change and its effect on coastal management

6.1 Introduction

The importance of climate change in the context of coastal management has generally been equated to the problems caused by an increase in mean sea level. This remains an important issue, particularly for low-lying areas where economically important assets are situated close to, or below, extreme tide level. However, recent winters in the UK have indicated a number of other potential impacts affecting the management of the coastline and its defences which may be more important, at least in the short-term. Such factors include an increased frequency of storms. Increased erosion of the coast may therefore be a greater concern in much of Scotland than flooding due to sea level rise. Much of Section 6.2 is taken from Brampton (1996).

6.2 Evidence of climatic change

6.2.1 General

The Intergovernmental Panel on Climate Change (IPCC) concluded that 'The balance of evidence from changes in global mean surface air temperature and from changes in geographical, seasonal and vertical patterns of atmospheric temperature, suggests a discernible human influence on global climate' (Houghton *et al.*, 1996). The conclusion of the IPCC rests on: (i) the physical effect of greenhouse gases on the atmosphere; (ii) observed climatic trends; and (iii) projections from global climate models.

The greenhouse effect results from certain gases in the atmosphere retaining heat that would otherwise be radiated into space. These greenhouse gases are relatively transparent to sunlight but absorb thermal infrared radiation emitted by the Earth's surface. The natural greenhouse effect already keeps the Earth over 30°C warmer than it otherwise would be; increasing concentrations of greenhouse gases warm the Earth still further.

The main greenhouse gases are carbon dioxide, methane, nitrous oxide and some industrial chemicals such as chlorofluorocarbons (CFCs) but also include water vapour. Significant modification of the atmosphere by human activities has occurred since the industrial Revolution. However, the magnitude of greenhouse gas emissions has increased enormously in recent decades. Increased carbon dioxide is the most important driver of global change contributing about 64% of the radiative forcing that produces global warming (Houghton *et al.*, 1996).

Global average surface air temperatures can be computed back to 1856. The record shows warming of about 0.5°C over the 140-year period to 1997, with the warmest year occurring in 1997 and the warmest six years all recorded since 1983 (Parker & Folland, 1995). The decade 1987-1996 has been 0.25°C warmer than the 1961-90 average.

6.2.2 Tidal and sea level change

Geomorphological evidence shows a long-term pattern of sea level rise relative to the land around much of the UK coast, stretching back over 10,000 years to the end of the last Ice Age. Generally rates of sea level rise during this period have been higher than they are today although there have been several periods of "stands" in level, or even periods of falling levels. However, since the end of the last Ice Age, the isostatic uplift of the land mass due to postglacial recovery (in mainland Scotland at least) has been occurring at a greater rate. The net result has been a fall in sea levels relative to the land level in most of Scotland, except for the Northern and Western Isles where gradual submergence has continued. Evidence for this is largely from geological features such as raised beaches which are a common occurrence around much of the Scottish coastline. The rate of isostatic uplift since the last Ice Age has been one of an exponential decrease and at present over much of Scotland the rate of increase in sea levels (eustatic increases) is now occurring at a slightly greater rate, i.e. sea levels are now increasing relative to land levels albeit at a very low rate (and certainly a much lower rate than say experienced on the south east coast of England). Whilst the Intergovernmental Panel on Climate Change (IPCC) (Houghton *et al.*, 1996) estimates a global mean sea level of 12-95cm higher than 1990 by the year 2100, the rise around the Scottish coast is expected to lie at the lower end of these values. Estimates by Hill *et al.*, (1999) indicate that the net mean rise in sea level around the Scottish coast by 2050 will be up to 30cm with nearly a third of the coastline only experiencing a rise up to 10cm, although the Shetland Isles may experience a net rise in sea level greater than 30 cm. These regional variations reflect differences in the rate of crustal uplift across the country which moderate or exacerbate, locally, the global rise in sea level. The term "net rise" means that land uplift rates are taken into account.

It is important to note that an increase in extreme tidal levels may not, in the short-term, be the same as an increase in mean sea levels. There is not only a long-term variation in the height and frequency of surges (as in wave heights, see Section 3.3), but also a change in the range of the astronomical tides. This latter aspect has been observed, for example in Newlyn, but not apparently explained. An increase in extreme tidal levels might be expected to increase the chances of wave overtopping of beaches and coastal defences or to increase dune erosion.

However, the evidence for this is far from conclusive. Recent research (Woodworth et al, 1991) carried out by the Proudman Oceanographic Laboratory analysed the long-term tide record from Newlyn in Cornwall. This has indicated the influence of the 18.6 year periodicity (caused by the precession of the plane of the Moon's orbit around the Earth, relative to the elliptical plane). During certain stages of this 19-year cycle, the mean tidal ranges increased by about 20mm/year, and it can be expected that the spring tidal ranges will increase by an even greater amount. This effect lasts for several consecutive years. During such periods, the effects on the upper parts of the beach would presumably be much the same as if mean sea level was rising by about half that amount, i.e. about 10mm/annum. Therefore it can be assumed that there would be periods of rapid beach erosion and landward recession during these times (presumably followed 9 years later by periods of beach accretion as high water levels decline). At present we are at the end of one of these rapid rise periods.

6.3 Effects on coastal management

6.3.1 Impact on beaches

General

One method for predicting shoreline erosion caused by sea level rise is known as the Bruun Rule (Bruun, 1983). This suggests that as sea levels rise, the beach will adjust to maintain a constant depth profile, i.e. the upper beach erodes, while the nearshore bed accretes. There is some evidence to suggest that this also happens in real life, but it should be realised that the method assumes a two-dimensional response when the development of a beach will almost always be three dimensional. The amount of sediment available is also a critical factor in the response of a beach to sea level rise, with those with a limited supply being more likely to retreat.

In the UK, the effect of sea level rise on beaches is probably not as great as those associated with changes in the wave climate, in the short term at least. An increase in the occurrence of very large waves will, for example, alter beach profiles or cause dune erosion which may take many months, or even years, to repair naturally. Conversely an increase in the occurrence of more modest waves, may be accompanied by a decrease in the largest wave heights. This would lead to a general steepening of the beach profile and a reduction in erosion. A change due to sea level rise may therefore go completely undetected.

Although a change in wave heights will cause changes to beach profiles, the long term evolution of the shoreline is almost always linked to changes in the longshore transport of beach sediments or, more precisely, the changes in transport from point to point along the coast. The longshore transport does depend on wave height, but more crucially on wave direction. The former influence, in the long term, can only increase or decrease the rate at which the coastline is eroding or accreting. However, a change in the "average" wave direction will often cause a change in the present trends of erosion and accretion (affecting both rates and patterns). At some locations, it has been found that erosion problems have recently occurred on stretches of coastline which have been stable or accreting for many years.

Impact on the beaches in Cell 2

An increase in sea level rise will have a significant effect upon the geomorphological response of the coastline within Cell 2. In general terms such changes are well documented, (e.g. Carter 1988). Only one published report, which assesses the effect of sea level rise on the coastline of Fife is currently available (McManus, 1990). This report considers climatic change and its effect on the coastline of Fife only in very general terms.

The response of much of the "soft" coastline, as for example, along much of the Angus coast, between Aberdeen and Collieston, and to the north of Peterhead, to climatic change is dependent upon the sediment budget, i.e. the balance between sediment supply and sediment loss, (Carter, 1988). Along the unprotected sand beach and dune systems such as St Andrews to Tentsmuir, parts of Barry Buddon, Montrose to St Cyrus, the River Don to the Sands of Forvie and to the north of Peterhead, coastal edge retreat will take the form of an erosional response. This erosion, induced by an increase in sea level, is a result of changes in wave refraction and a decrease in distance to the zone of breaking, due to deeper water. Waves and currents also tend to act higher up the beach profile.

In many of the beach areas, such as to the north of Peterhead, landward retreat of the coastal edge will not cause a serious problem as there is a wide buffer zone containing a large supply of available beach material. The main problem area will be where development has encroached onto the immediate coastal hinterland. Industrial development, such as that at St Fergus, will become more vulnerable. Fortunately there are few other significant industrial developments which will be directly affected. The other main problem area will be erosion of the many golf courses occurring within the coastal links.

On parts of the coastline fronted by shingle ridge beaches, such as to the north of Milton Ness and at Inverbervie, overwashing of the shingle ridge is likely to increase. This will cause rollover with beach material progressively transferred from the shoreface, pushed over the crest and onto the back face thereby causing a landward retreat. The average rate of retreat is approximately proportional to the rate of sea level rise. Where there is a sufficient volume of shingle material available the crest of the shingle beach will increase in elevation to accommodate sea level rise. However, if beach material is sparse an increase in elevation is at the expense of the width of the shingle ridge leading to an increase in the risk of breaching. The most vulnerable area to this type of response is at Inverbervie where housing occurs behind the crest at the southern end of the bay.

The extent of coastal edge retreat will vary all along the this coastline. Although simplified predictions exist, (e.g. Bruun, 1983), actual retreat rates will depend upon a whole range of interrelating factors, the effects of which can not be predicted quantitatively. Such changes will however be gradual, as there will not be a sudden change in sea level, with the coastal regime gradually evolving due to these changes.

With any increase in sea level, there is also an increase in the frequency and extent of any coastal flooding. Areas presently affected by coastal inundation, for example the Eden Estuary, the River Dee just upstream of Aberdeen Harbour and at Newburgh, will experience an increase in the frequency of such events.

6.3.2 Impacts on man-made defences

General

A study into the effects of sea level rise on coastal structures was carried out by Townend (1994). This showed that the effect of sea level rise on design parameters such as armour weight and run-up depended very much upon the location of the structure in the surf zone and whether waves were breaking or non-breaking at the structure. For instance with breaking waves rock armour weight requires an increase of over 100% for an increase in water depth of only 10%. However, in shallow water where waves are not breaking there is a slight reduction in the required armour weight and in the level of run-up with increases in sea level due to reduced wave shoaling. The effect of sea level rise will always cause an increase in the overtopping of defences irrespective of wave condition.

Possibly of greater importance in the design of coastal structures such as breakwaters and seawalls is the impact of increased storm activity. For example, the size of stable rock armouring on a revetment or breakwater depends on the cube of the design wave height. An increase in extreme wave heights of only 1% each year could, in a decade, lead to a requirement for armour unit weights to be some 38% heavier to achieve the same degree of safety.

In most situations, defences first fail "functionally", allowing erosion or flooding of the land behind. Occasionally, however a defence will suddenly fail "structurally", leading to a much greater danger to life and property, for example the collapse of the seawall at Towyn in North Wales. In most cases, the failure of defences results from a combination of factors, e.g. low beach levels, a high tide and large waves from a limited directional sector. A gradual change in the probability of occurrence of just one of these parameters may therefore not be apparent for many years.

Impact on man-made defences in Cell 2

It is unlikely that there will be any significant increase in the occurrence of damage to structures such as rock revetments in the short term, due to the relatively small climatic changes occurring. However, the main locations where such increases are likely to arise are where present defences have a low threshold to damage, such as the various gabion structures at the mouth of the River Eden, and where structures are presently in a poor condition, such as some of the older seawalls at Peterhead and some of the small fishing villages south of Stonehaven.

The occurrence and volume of wave overtopping of present structures will increase and is likely to be more obvious than an increase in the occurrence of damage to structures. This will have particular significance at places such as Inverallochy where the revetment is low with housing present close to the coastal edge, or at Stonehaven where overtopping of the seawall is an existing problem.

Where coastal engineering works restrict landward recession, beach profile levels will drop as the mean low and high water levels attempt to migrate landward. This is already being noticed at Aberdeen beach, where comparison of the mean high and low waters between 1865 and 1954, (Stapleton & Pethick, 1996) indicates a narrowing of the intertidal zone. Similar effects are likely to be most noticeable where sand beaches are backed by linear "hard" defences such as at Stonehaven and Carnoustie. Any decrease in beach levels will result in an increased risk of damage or failure of any structure as more severe wave conditions will reach the defence.

6.3.3 Other effects

There are a number of other climatic factors which may affect coastline evolution and hence management techniques. Two of these are discussed below. In each case little is known of the extent of any variations in these climatic factors and whether these are of significance in managing the coast.

Rainfall

There is an observed variation in the rainfall patterns occurring in the UK. In the south of England an oscillation of about 40 years period has been observed. There is anecdotal evidence that a 20-30% increase in rainfall has been recorded in central Scotland over the last 25-30 years. As rainfall increases, a number of effects are likely to occur at the coastline:

- De-stabilisation of soft cliffs

  Cliff falls are usually caused by a combination of marine erosion, e.g. undercutting their front face, and geotechnical problems, e.g. rotational slips. The latter effect is increased by greater rainfall and hence higher run-off, higher water tables etc. There are probably no areas within Cell 2 where any increase in cliff falls will result in an increase in the supply of beach sediment.

- Increased river flows
  In many parts of the world, rivers still bring large quantities of sand and gravel to the coast, providing fresh supply. Increased river flows would increase the capacity of the river to transport sediment. However, the Cowie Water at Stonehaven is the only river which is likely to supply an appreciable volume of sediment to the beach system within this Cell.

- Impacts on sand transport on beaches
  In locations where a beach is affected by surface water run-off from land, there are often localised erosion problems, e.g. around outfalls. The frictional resistance of sand is reduced by the water, making it easier to be mobilised by waves and currents. It is therefore likely that increased rainfall will tend to cause localised beach erosion.

- Impacts on dune building
  Wet sand on the foreshore will be much less easily transported by winds than if it is dry, reducing the supply to dunes. However, many dune binding grasses suffer in drought conditions, and are generally healthier in moister climates. This would help to increase the trapping efficiency, and encourage them to colonise new areas more quickly. It is not clear, therefore, whether increased rainfall will assist dune growth or be detrimental to it.

Changes in wind
As well as changes in wind conditions altering waves, discussed earlier, there are other direct effects which may affect the coastline:

- Aeolian sand transport
  Strong winds are capable of transporting large quantities of sand, both along the coastline and perpendicular to it. The former effect can add to, or counteract, wave induced longshore drift, but tends to take place at higher levels on the beach profile. Onshore transport by wind typically dominates over offshore movement. This is partly because winds blowing over the sea are stronger (less affected by friction) than those blowing offshore.

  A change in wind strengths or directions may also alter existing patterns of sand transport. It is likely that this will be most noticeable in changes in dunes, rather than on the beaches themselves. Large dune complexes such as are found along much of the coastline of this Cell are likely to be affected most from such changes.

Much of the above discussion on climatic change and its impact on coastal response is based on logical argument rather than well documented case histories.

The impact of climatic change on the coastline of Cell 2 is likely to be noticeable given the amount of “soft” beach areas and the relatively high anthropogenic usage of the coastal zone relative to other cells. However, the complexity of the coastal and nearshore zone makes it difficult to predict morphological changes due to the range of inter-relating parameters which affect this zone. To identify and quantify the effect on the coastline of changes to any one, or a number of, these parameters would require good quality, long term data to validate predictive methods and to identify changes in the marine (i.e. hydraulic) climate.

Trying to separate longer term climate change effects from those caused by “normal” fluctuations in weather is a major challenge. There is a clear need for monitoring of the coastline, not only to understand the processes, but to provide a long term data set for future generations trying to deal with the effects of potentially more dramatic climate changes.

7 *References and Bibliography*

7.1 References

Ashmore P J (1994). Archaeology and the coastal erosion zone. Towards a Historic Scotland policy. Historic Scotland Report.

Bacon S & Carter D J T (1991). Wave climate changes in the North Atlantic and North Sea. Journal of Climatology, **2**, 545-558.

Barne J H, Robson C F, Kaznowska S S, Doody J P and Davidson N C (Eds) (1996). Coasts and Seas of the United Kingdom. Region 3. North-east Scotland: Cape Wrath to St Cyrus. Joint Nature Conservation Committee, Peterborough.

Barne J H, Robson C F, Kaznowska S S, Doody J P and Davidson N C (Eds) (1997). Coasts and Seas of the United Kingdom. Region 4. South-east Scotland: Montrose to Eyemouth. Joint Nature Conservation Committee, Peterborough.

Binnie & Partners (1991). Fraserburgh Long sea outfall feasibility study. Volume 1. Grampian Regional Council. Department of Water Services.

Brampton A H (1996). Climatic change and its effects on coastal management. In *Climatic change offshore N.W. Europe*. An assessment of impacts of changing meteorological and oceanographic (Metocean) conditions on offshore activities. Conference at Imperial College of Science, Technology and Medicine, 18 April 1996. Society for Underwater Technology.

British Oceanographic Data Centre (1991). United Kingdom Digital Marine Atlas.

Bruun P M (1983). Sea level rise as a cause of shore erosion. Journal of the Waterways, Harbours and Coastal Engineering Division. ASCE, **88**, No WW1. 117-130.

Buchan G M (1976). Dynamics of a river mouth spit and related processes in Aberdeen Bay. Unpublished PhD thesis, University of Aberdeen.

Buller A T, McManus J & Williams D J A (1971). Investigations in the estuarine environments of the Tay: Physical aspects: an interim report. Tay Estuary Research Centre. Dundee University. Research Report No. 1.

Caledonian Geotech. (1987) Tayside Regional Council, Coastal erosion study. Phase 2. Final report.

Cameron I B & Stephenson D (1985). British Regional Geology. The Midland Valley of Scotland. 3rd edition. HMSO, Edinburgh.

Carter R W G. (1988) Coastal Environments. Academic Press, London.

CIRIA/CUR (1991). The use of rock in coastal and shoreline engineering. CIRIA Special Publication 83/CUR Report 154. Construction Industry Research and Information Association.

CIRIA (1996). Beach management manual. CIRIA Special Publication 153. Construction Industry Research and Information Association.

Coles S G & Tawn J A (1990). Statistics of coastal flood prevention. Philosophical Transactions of the Royal Society of London, **332**, 457-476.

Department of the Environment (1995). Policy guidelines for the coast. Department of the Environment, London.

Dixon M J & Tawn J A (1994). Extreme sea levels at the UK A-class sites: Optimal site-by-site analysis. Proudman Oceanographic Laboratory Internal Document No. 65.

Dixon M J & Tawn J A (1997). Spatial analysis for the UK coast. Proudman Oceanographic Laboratory Document No. 112.

Dodd N & Brampton A H (1995). Wave transformation models: a project definition study. HR Wallingford Report SR 400. HR Wallingford, Wallingford.

Doody J P, Johnston C & Smith B (1991). Directory of the North Sea coastal margin. Joint Nature Conservation Committee. Peterborough.

Graff J (1981). An investigation of the frequency distributions of annual sea level maxima at ports around Great Britain. Estuarine, Coastal and Shelf Science, **12**, 389-449.

Hay, W D. (1980) Survey of coastline within Grampian Region. Grampian Regional Council, Department of Roads.

Hill M O, Downing T E, Berry P M, Coppins B J, Hammons P S, Marquiss M, Roy D B, Telfer M G and Welch D. (1999). Climate changes and Scotland's natural heritage: an environmental audit. Scottish Natural Heritage Research, Survey and Monitoriong Report No 132.

Houghton, J T, Jenkins, G J and Ephraums, J J (1990). Eds: Climate Change. The Intergovernmental Panel on Climate Change Scientific Assessment.. Cambridge University Press, Cambridge.

Houghton J T, Meiro Filho L G, Callander B A, Harris N, Kattenberg A & Maskell K (Eds) (1996). Climate Change 1995: The Science of Climate Change. Contribution of Working Group 1 to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

HR Wallingford (1969). Siltation in Arbroath Harbour. HR Report EX 446. HR Wallingford, Wallingford.

HR Wallingford (1988a) Aberdeen Harbour. Report on Phase II studies. Volume I. HR Report EX 1759. HR Wallingford, Wallingford.

HR Wallingford (1988b) Aberdeen Harbour. Report on Phase II studies. Volume II, Appendices 1 and 2. HR Report EX1759. HR Wallingford, Wallingford.

HR Wallingford (1988c). Coast protection study - Barry Buddon, Tayside. HR Report EX1786. HR Wallingford, Wallingford.

HR Wallingford (1989). Barry Buddon Ranges, Tayside. Wave and beach study. HR Report EX 1867. HR Wallingford, Wallingford.

HR Wallingford (1991). Barry Buddon Ranges. Design of a rock revetment. Vol 1: Text; Vol 2: Tables, Figures, Plates and Appendices. HR Report Ex 2211. HR Wallingford, Wallingford.

HR Wallingford (1992a) St Andrews outfall marine study. Dye tracing and profiling in St Andrews Bay. HR Report EX 2679. HR Wallingford, Wallingford.

HR Wallingford (1992b). St Andrews outfall marine study. Assessment of data and pilot 2-D model. HR Report EX 2626. HR Wallingford, Wallingford.

HR Wallingford (1993a). Coastal Management: Mapping of littoral cells. HR Wallingford, Report SR 328. HR Wallingford, Wallingford.

HR Wallingford (1993b). Coastal erosion, The Faulds, Montrose. Initial appraisal study. HR Report EX 2828. HR Wallingford, Wallingford.

HR Wallingford (1994). St Andrews Links, Scotland. A study of coastal erosion. HR Report EX 2562. HR Wallingford, Wallingford.

HR Wallingford (1995). Montrose Bay Coastal Erosion Study - Phase II. Tidal modelling of Montrose and Lunan Bays. HR Wallingford Report EX 3195. HR Wallingford, Wallingford.

HR Wallingford (1997). Coastal Cells in Scotland. Scottish Natural Heritage Research, Survey and Monitoring Report No. 56.

Hydrographer of the Navy (1963). North Sea. Flamborough Head to Pentland Firth. Tidal Stream Atlas.

Ibsen M L (1994). Evaluation of the temporal distribution of landslide events along the south coast of Britain between Straight Point and St Margarets. Unpublished M Phil thesis, University of London.

Jarvis J & Riley, C. (1987) Sediment transport in the mouth of the Eden estuary. Estuarine, Coastal and Shelf Sciences, **24**, 463-481.

Jenkinson A F & Collison F P (1977). An initial climatology of gales over the North Sea (unpublished). Meteorological Office 13, Branch Memorandum No. 62, Bracknell.

Lamb H H & Weiss I (1979). On recent changes of the wind and wave regime of the North Sea and the outlook. Fachliche Mittyerluugen. AMT fur Wehrgeophysik, No. 194, March 1979.

Legget I M, Beiboer F L, Osborne M J & Bellamy I (1996). Long term Metocean measurements in the Northern North Sea. In *Climate change offshore N.W. Europe*. An assessment of the impacts of changing meteorological and oceanographic (Metocean) conditions on offshore activities. Conference at Imperial College of Science, Technology and Medicine, 18 April 1996. Society for Underwater Technology.

Lynagh N (1996). Weather and climate variability since prehistoric times and recent indications of continuing fluctuations in the NE Atlantic. In *Climate change offshore N.W. Europe*. An assessment of the impacts of changing meteorological and oceanographic (Metocean) conditions on offshore activities. Conference at Imperial College of Science, Technology and Medicine, 18 April 1996. Society for Underwater Technology.

MAFF (1995a). Shoreline Management Plans. A guide for coastal defence authorities. MAFF, London.

MAFF (1995b). UK Dredged Material Licence Database. MAFF, London.

Marine Information and Advisory Service (MIAS) (1982). MIAS catalogue of instrumentally measured wave data. MIAS Reference Publication No 1, IOS, Wormley, Surrey.

Mather A S, Smith J S & Rose N (1978) The Beaches of North East Scotland. Aberdeen University, Department of Geography. Report for the Countryside Commission of Scotland.

McManus (1990). The greenhouse effect, global warming and sea level rise: some anticipated impacts on Fife. Report to Fife Council.

Metocean (1994). Energy industry Metocean data around the UK. Metocean Report No 537.

Mitchell P (1997). Coastal erosion on the Angus coastline. Report to Scottish Natural Heritage.

Pallett N (1963). Building the new seawall at Aberdeen. Engineering, **196**, 306.

Parker D E & Folland C K (1995). Comments on the global climate of 1994. Weather, **50**, No 8, August 1995.

Ritchie, W. (1979) The beaches of Fife. Aberdeen University, Department of Geography. Report for the Countryside Commission of Scotland.

Scottish Office (1996). Scotland's coast. A discussion paper. HMSO, Edinburgh.

Scottish Office (1997). National Planning Policy Guideline (NPPG) 13. Coastal Planning. HMSO, Edinburgh.

Spencer N E & Woodworth P L (1993). Data holdings of the Permanent Service for Mean Sea Level. Bidston Observatory, Birkenhead.

Stapleton C & Pethick J (1996). Coastal processes and management of Scottish estuaries. III. The Dee, Don and Ythan Estuaries. Scottish Natural Heritage Review No 52.

Steers J (1973). The coastline of Scotland. Elsevier, Kidlington.

Stephenson D & Gould D (1995). British Regional Geology. The Grampian Highlands (4th edition). HMSO for the British Geological Survey.

Townend I H (1994). Variations in design conditions in response to sea level rise. Institution of Civil Engineers Proceedings. Water, Maritime and Energy, **106**, 205-213.

Woodworth P L (1987) Trends in UK mean sea level. Marine Geodesy, **11**, 57-87.

Woodworth P L, Shaw S M & Blackman D L (1991). Secular trends in mean tidal range around the British Isles and along the adjacent European coastline. Geophysical Journal International, **104**, 563-609.

Wright, R. (1981) The beaches of Tayside. Aberdeen University, Department of Geography. Report for the Countryside Commission for Scotland.

Figures 1-24

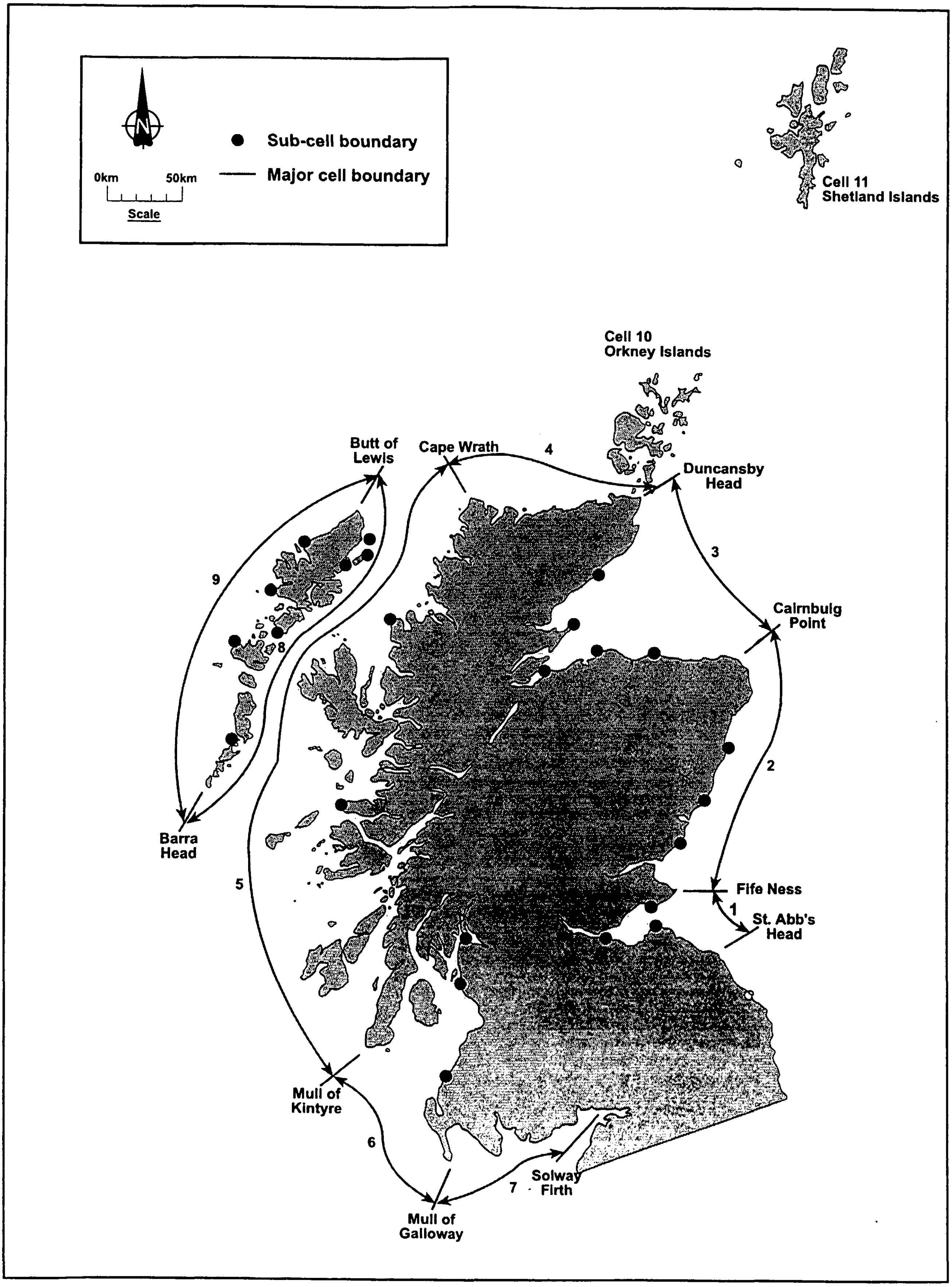


Figure 1 Coastal Cells in Scotland

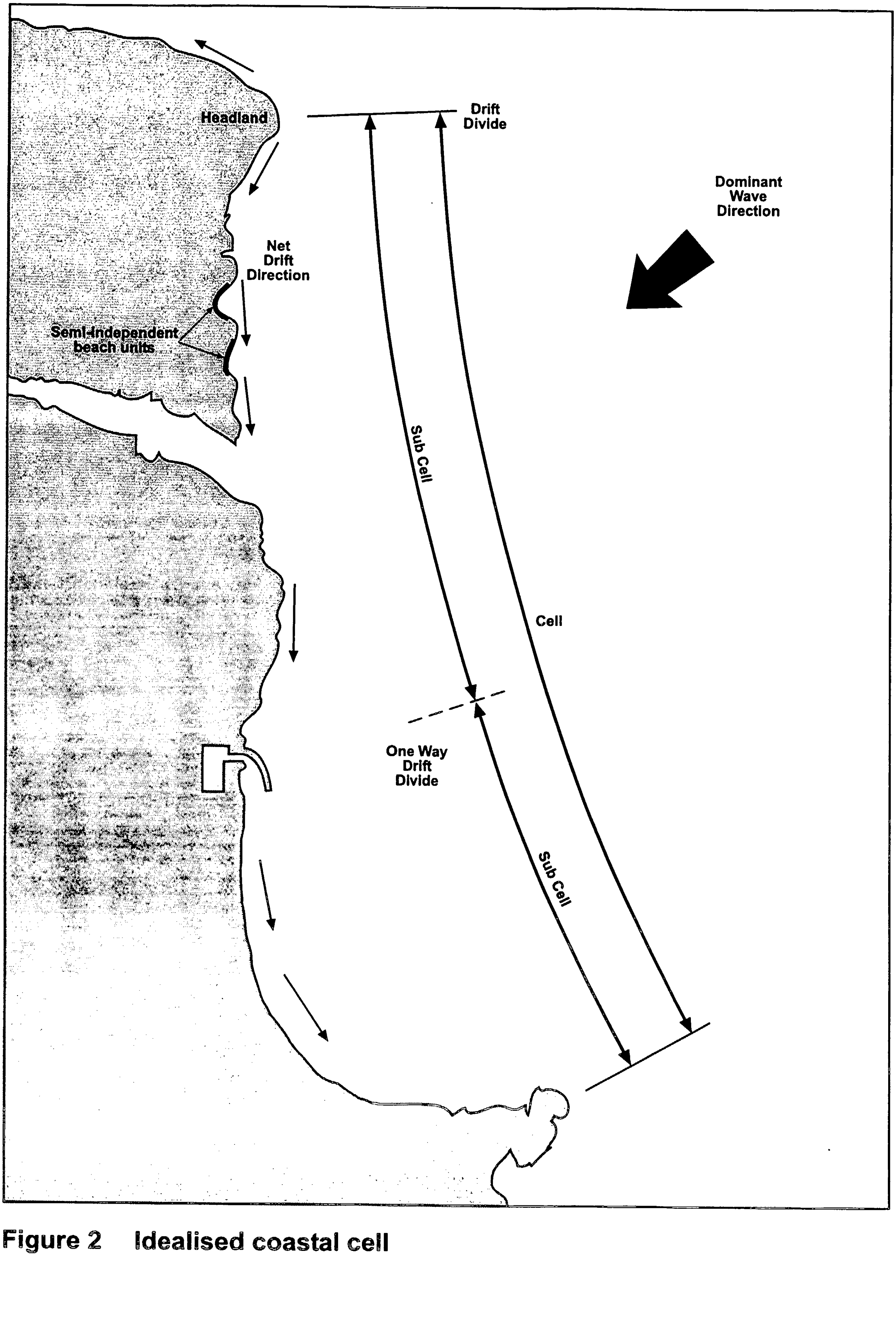


Figure 2 Idealised coastal cell

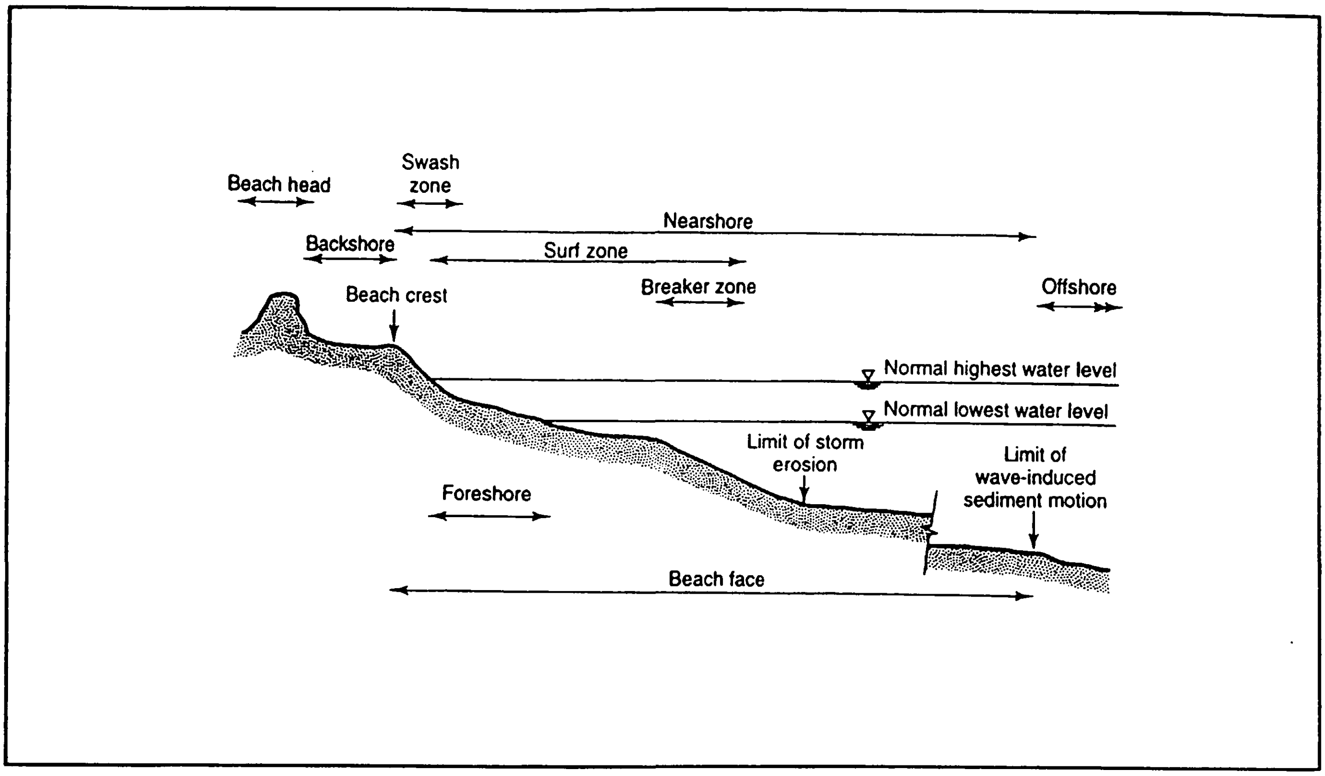


Figure 3 General beach profile and littoral zone

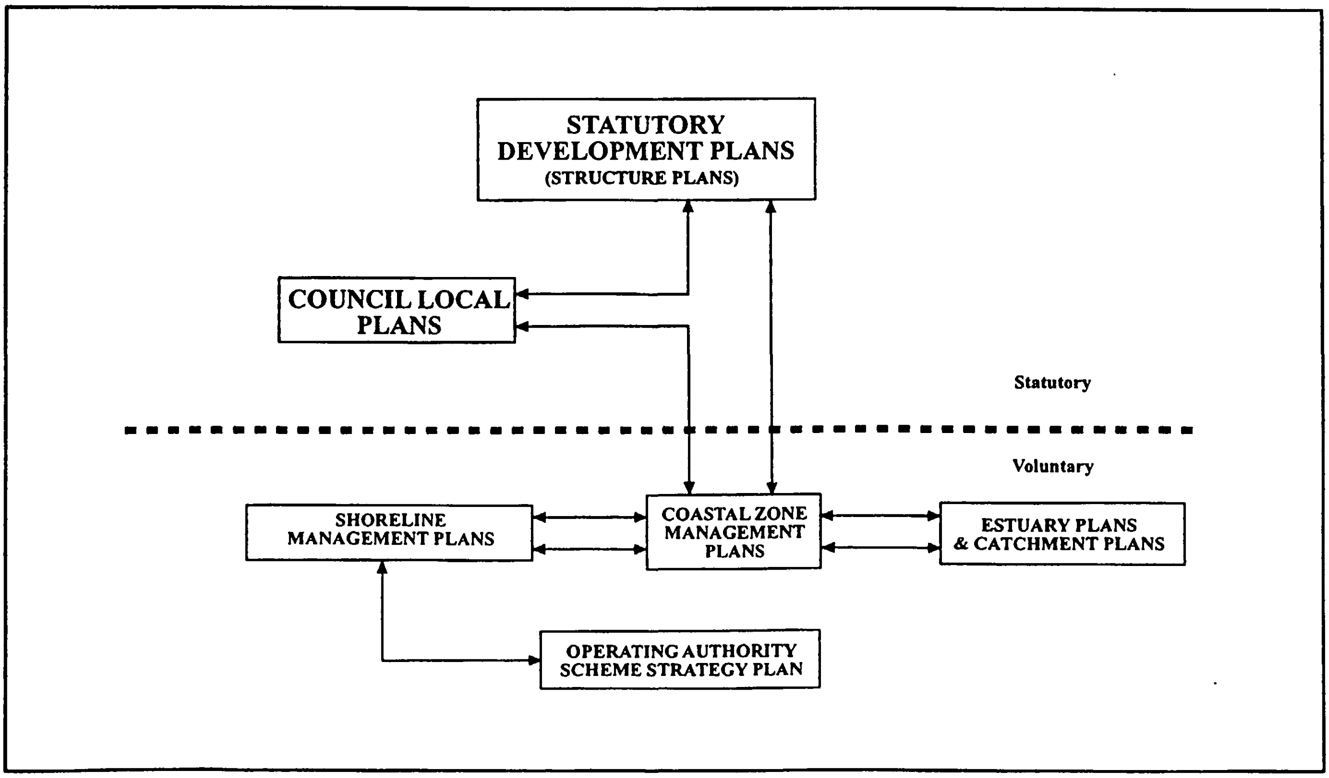


Figure 4 Relationship between coastal initiatives

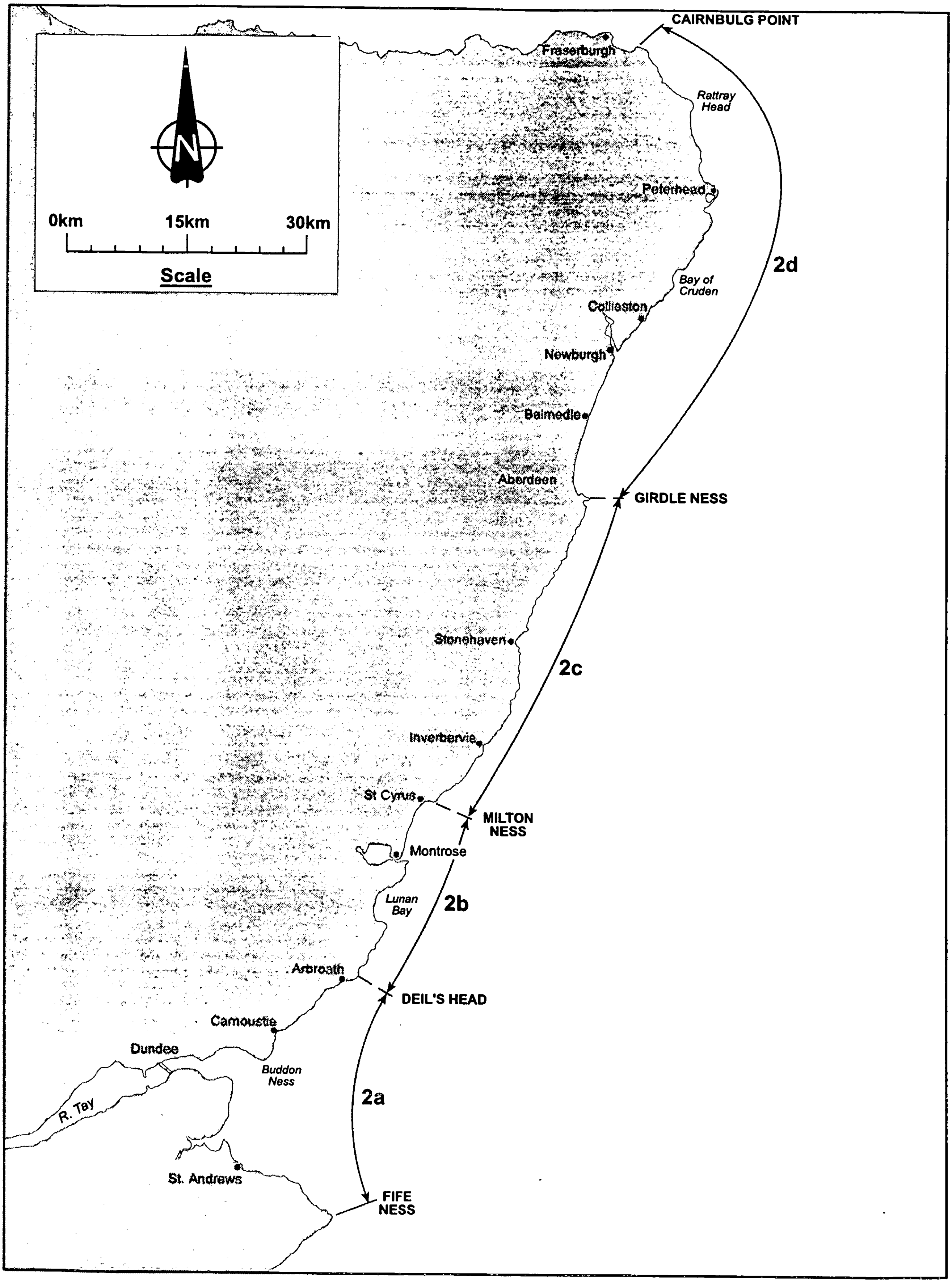


Figure 5 Cell 2 - Fife Ness to Cairnbulg Point

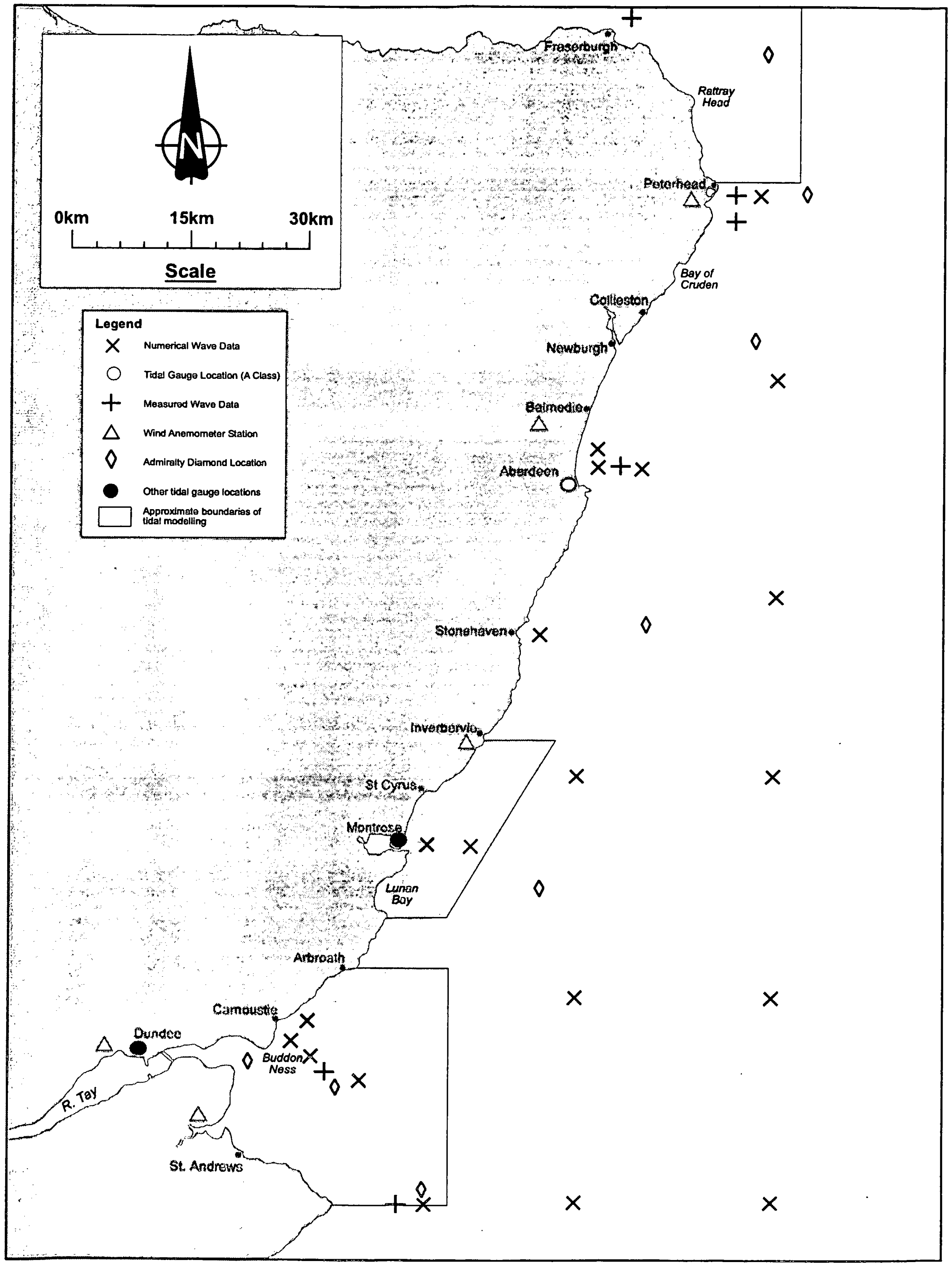


Figure 6 Cell 2 - Location of wind, tidal and wave data

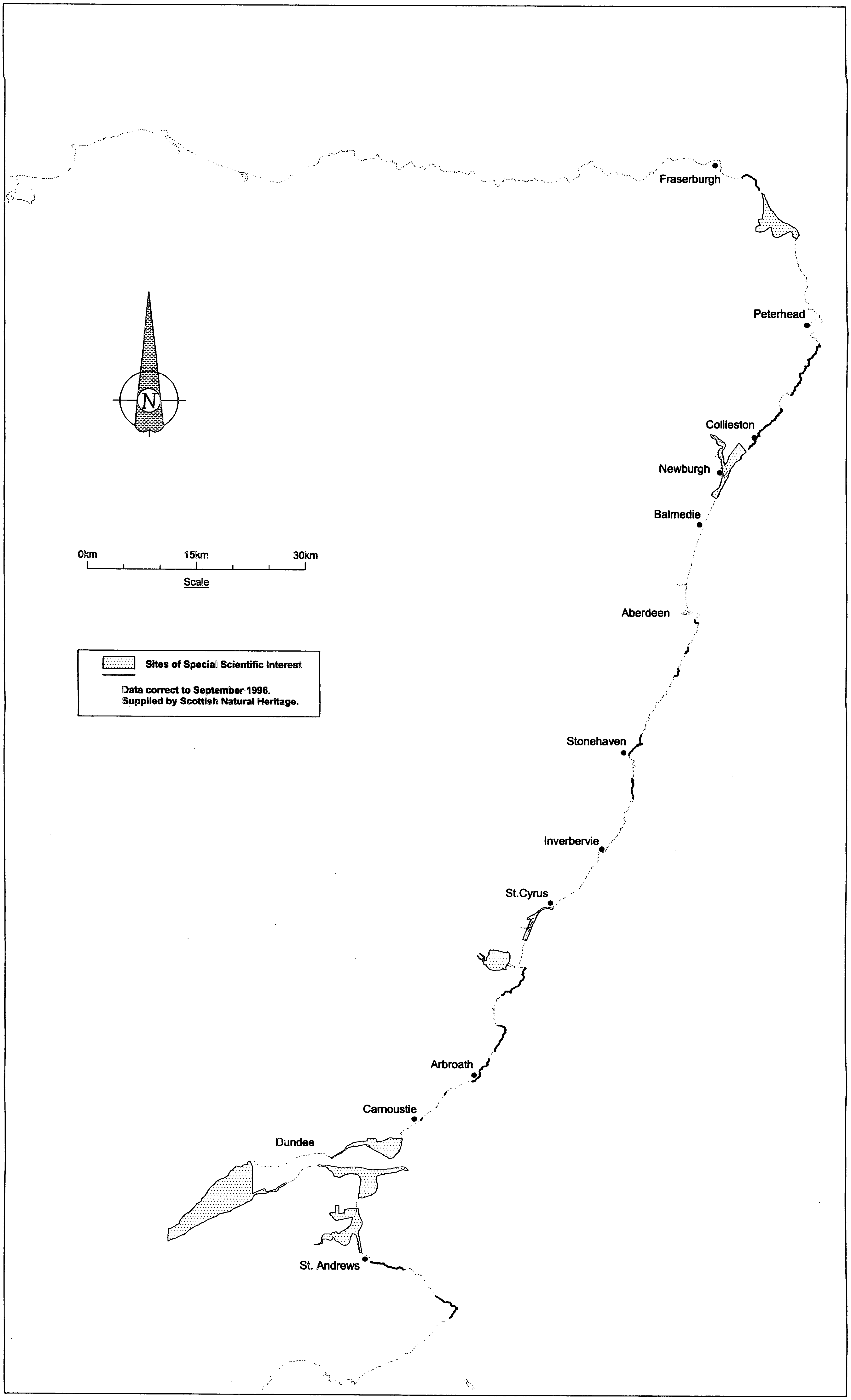


Figure 7 Cell 2 - Location of Sites of Special Scientific Interest

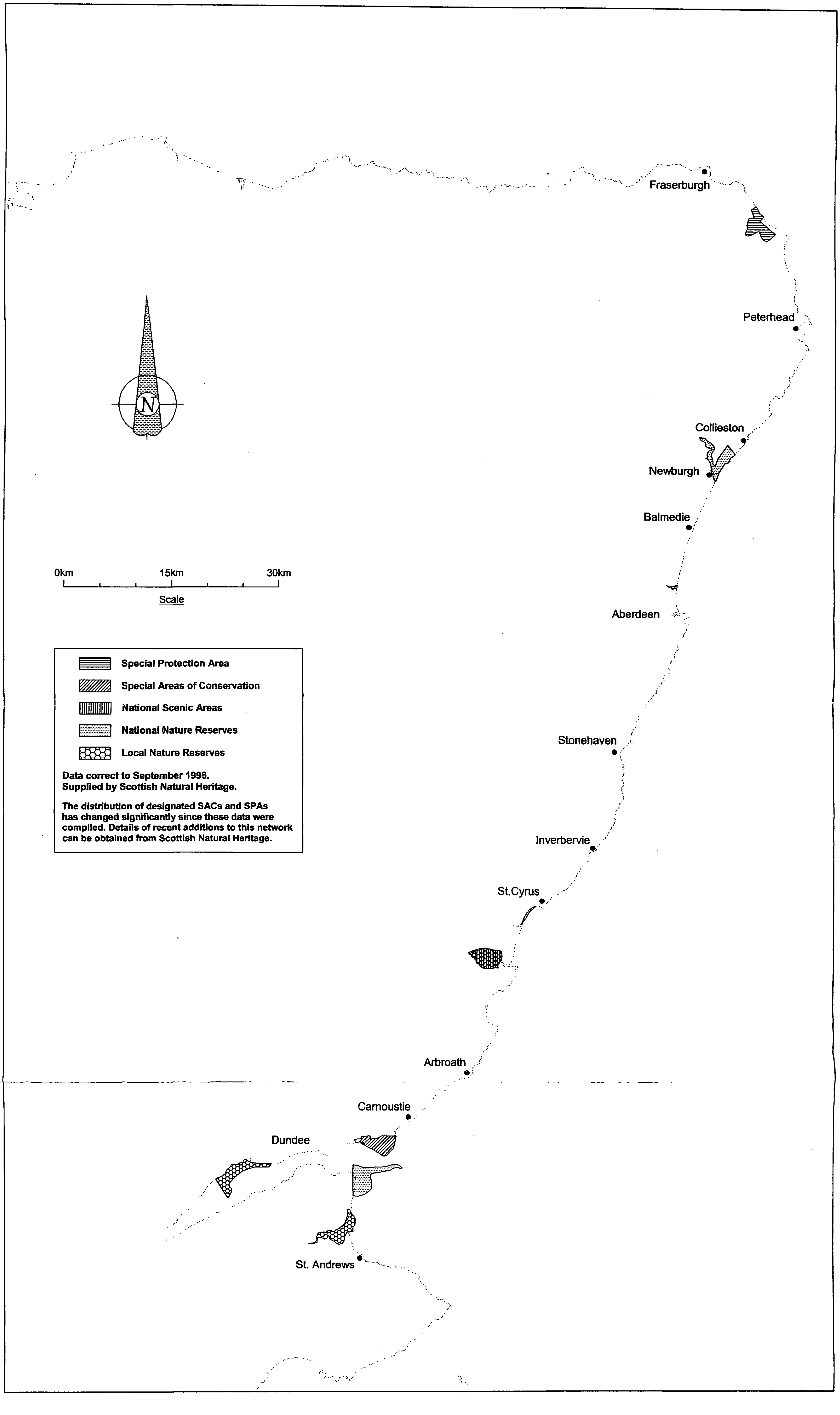
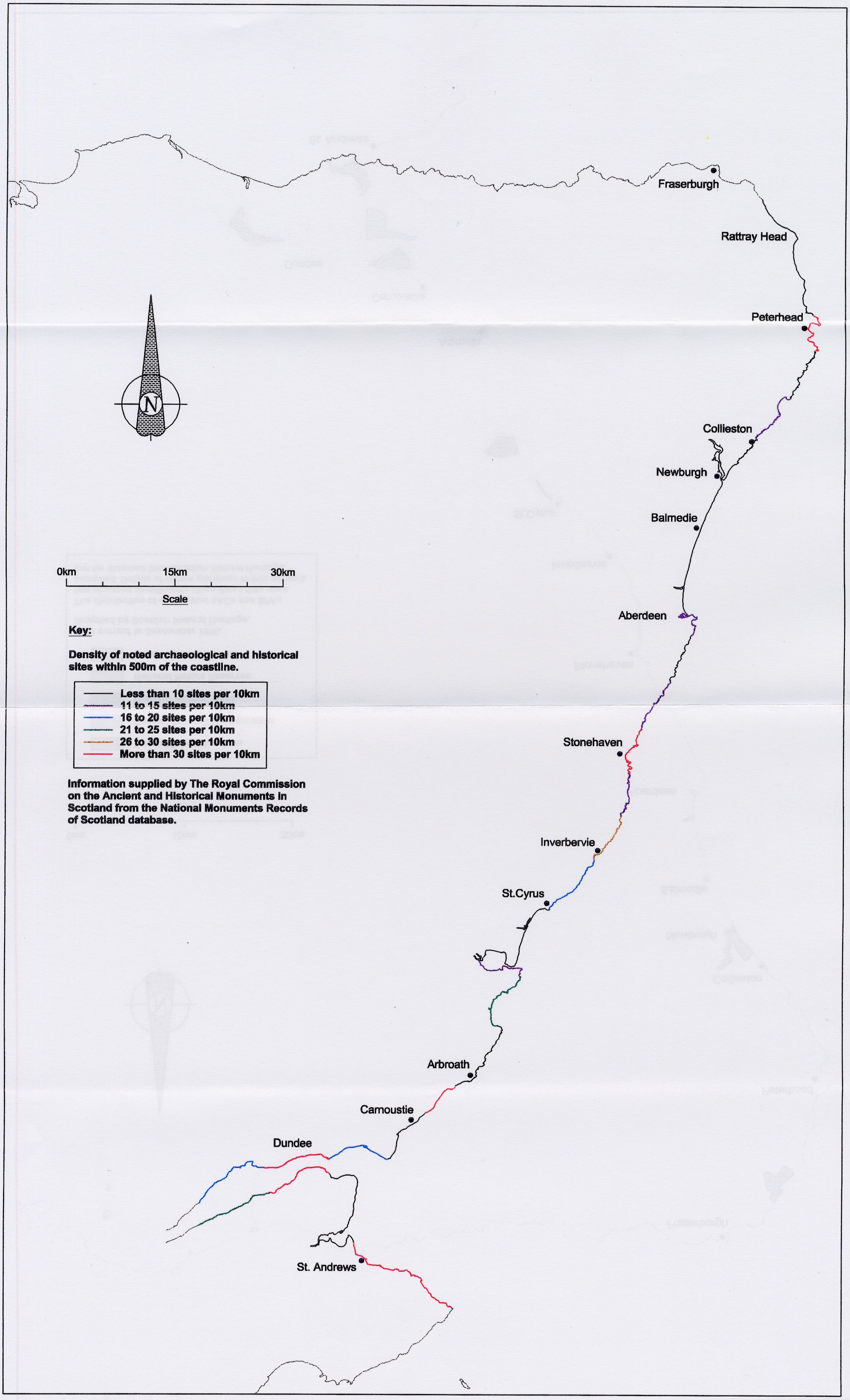


Figure 8 Cell 2 - Location of sites of natural heritage importance (other than SSSIs)

Figure 9 Cell 2 - Density of noted archaeological and historical sites



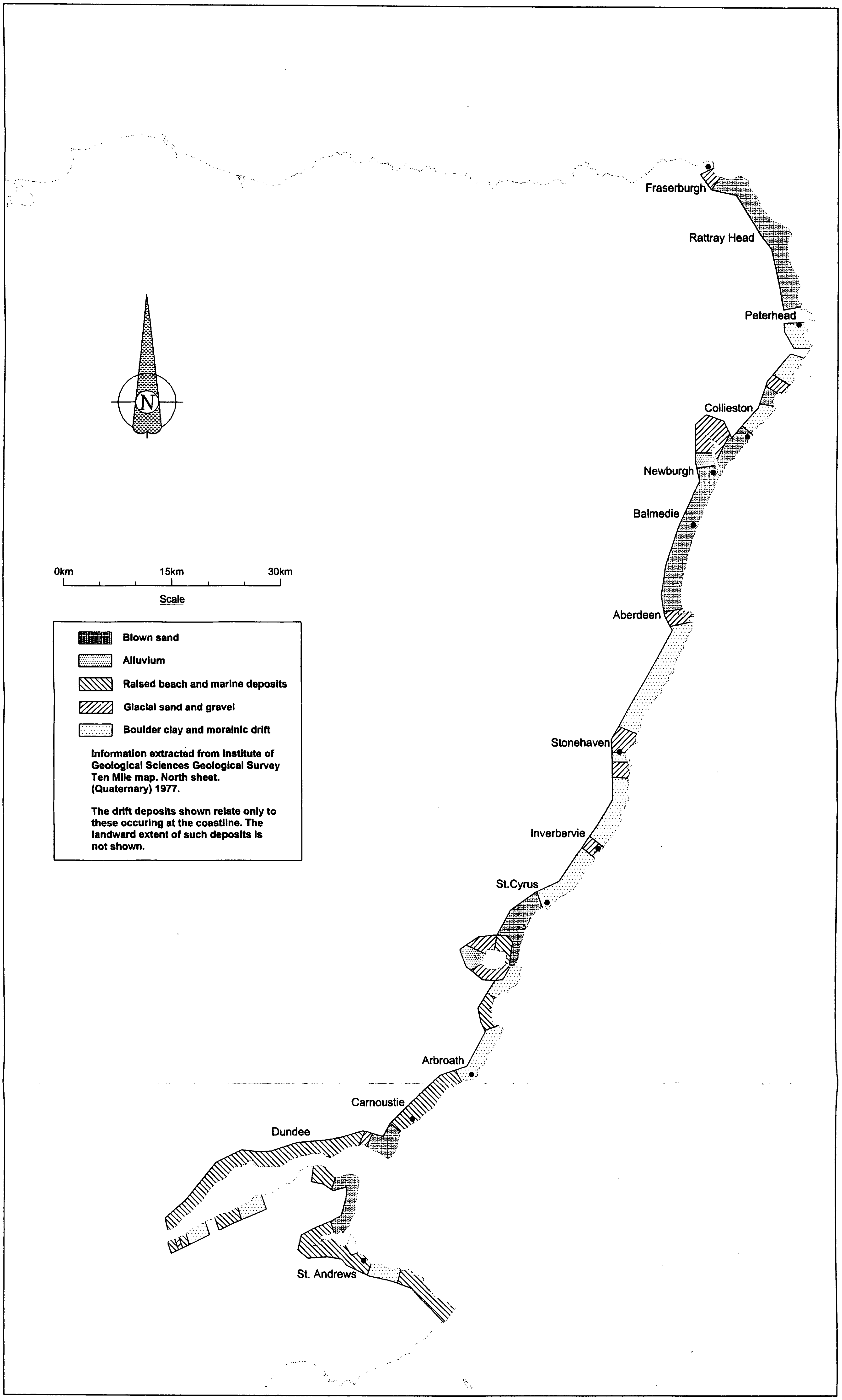


Figure 10 Cell 2 - Drift deposits

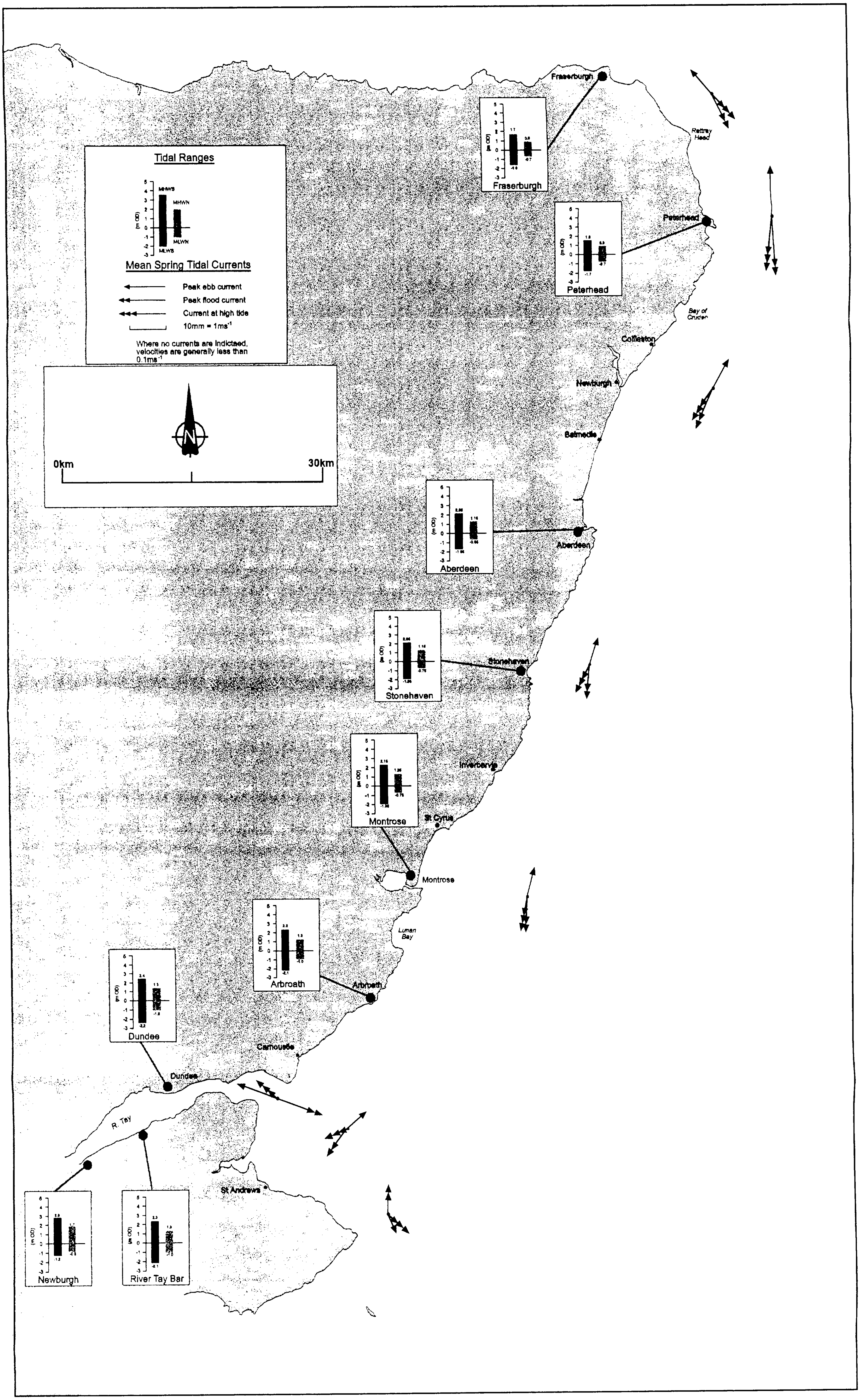


Figure 11 Cell 2 - Tidal levels and current information

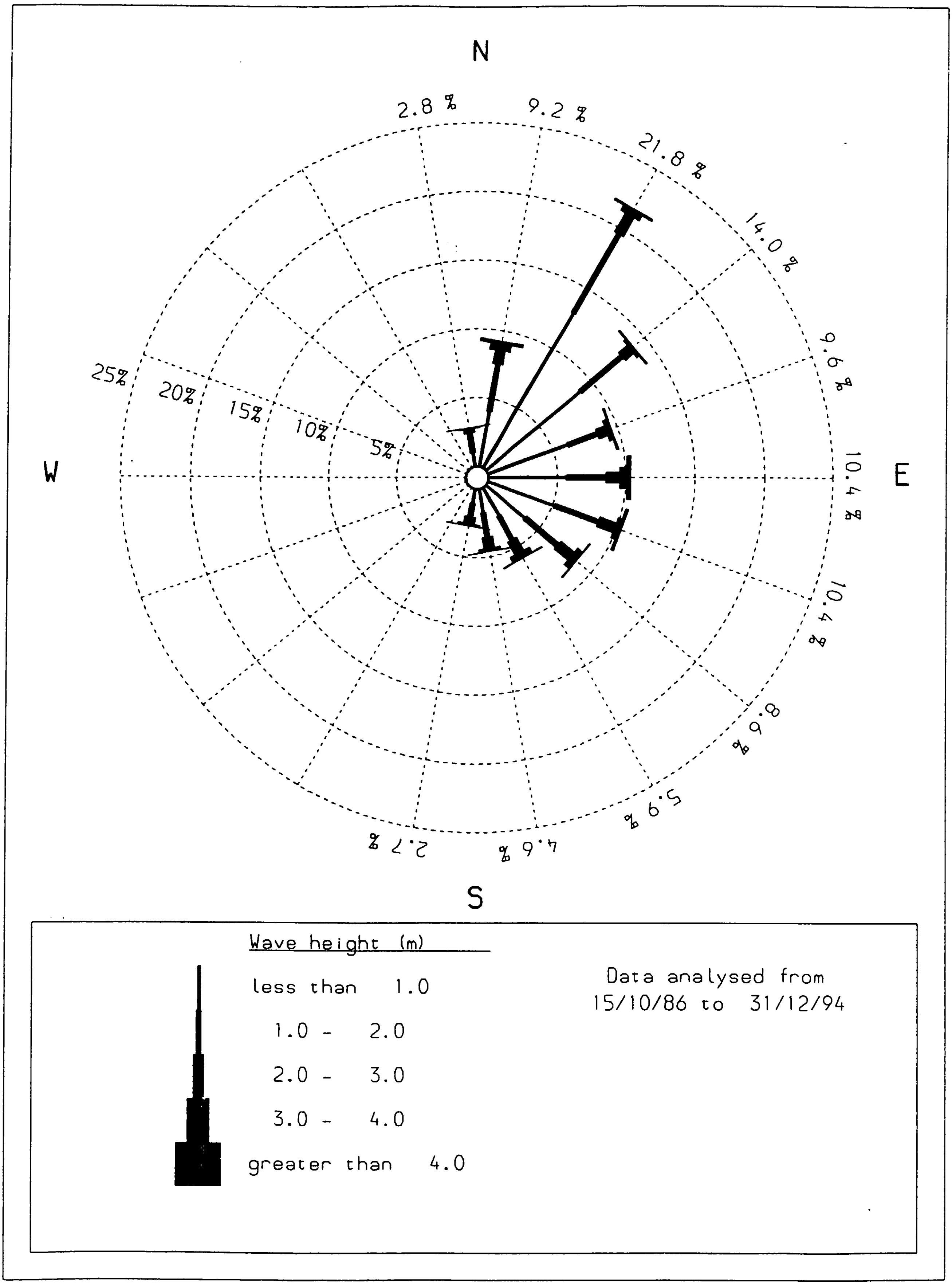


Figure 12 Offshore total wave climate east of Tay Estuary

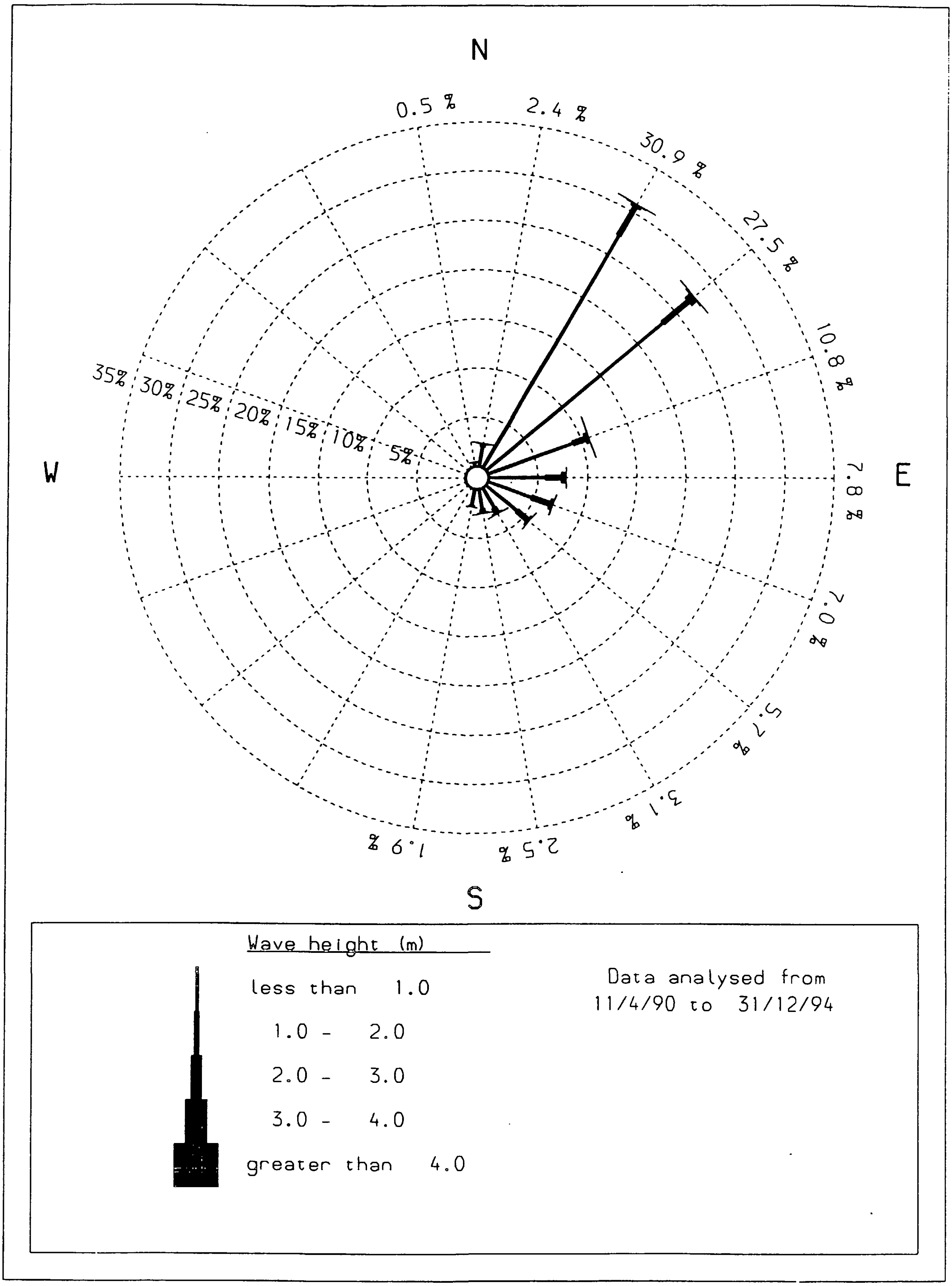


Figure 13 Offshore swell wave climate east of Tay estuary

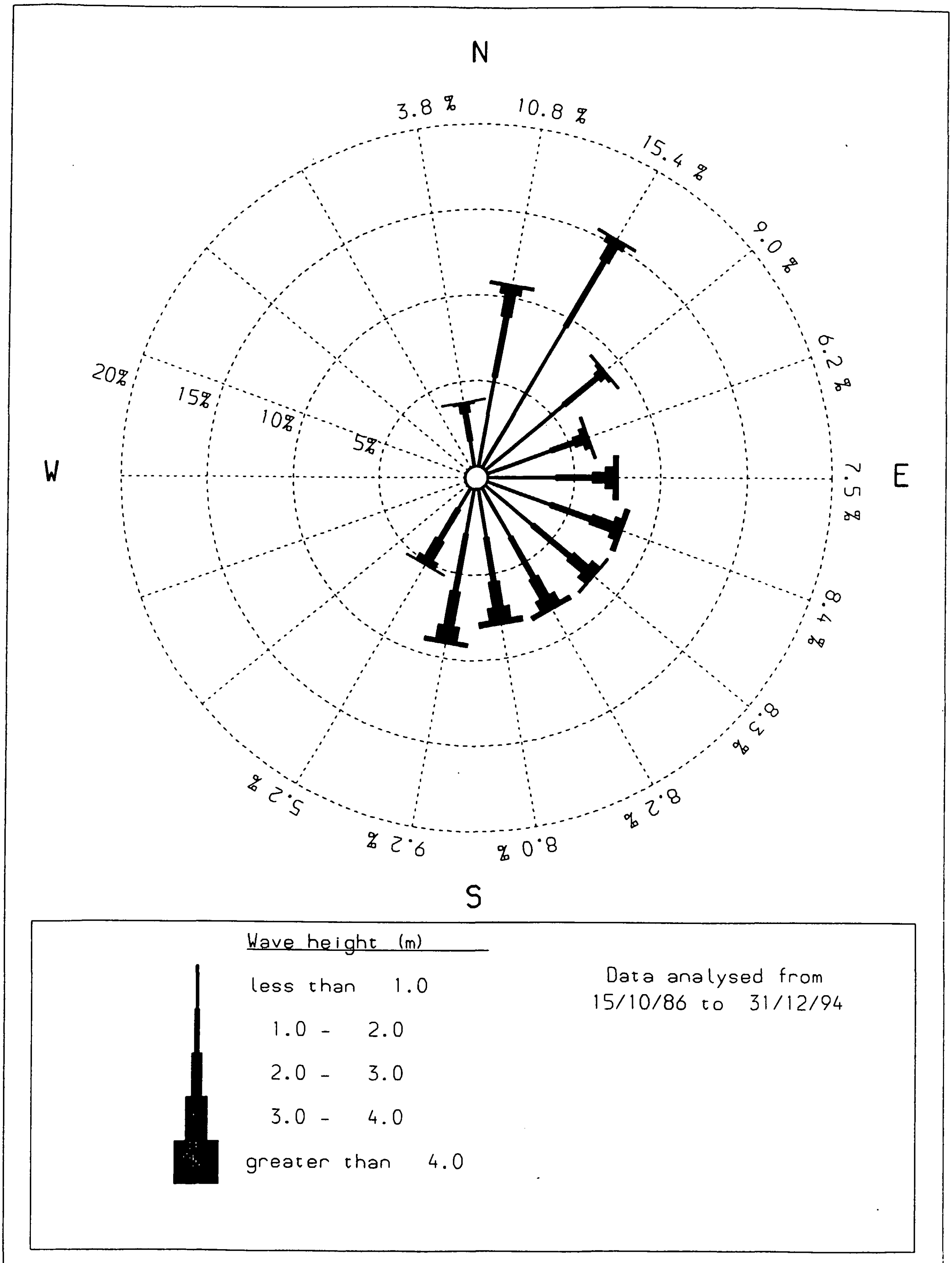


Figure 14 Offshore total wave climate east of Aberdeen

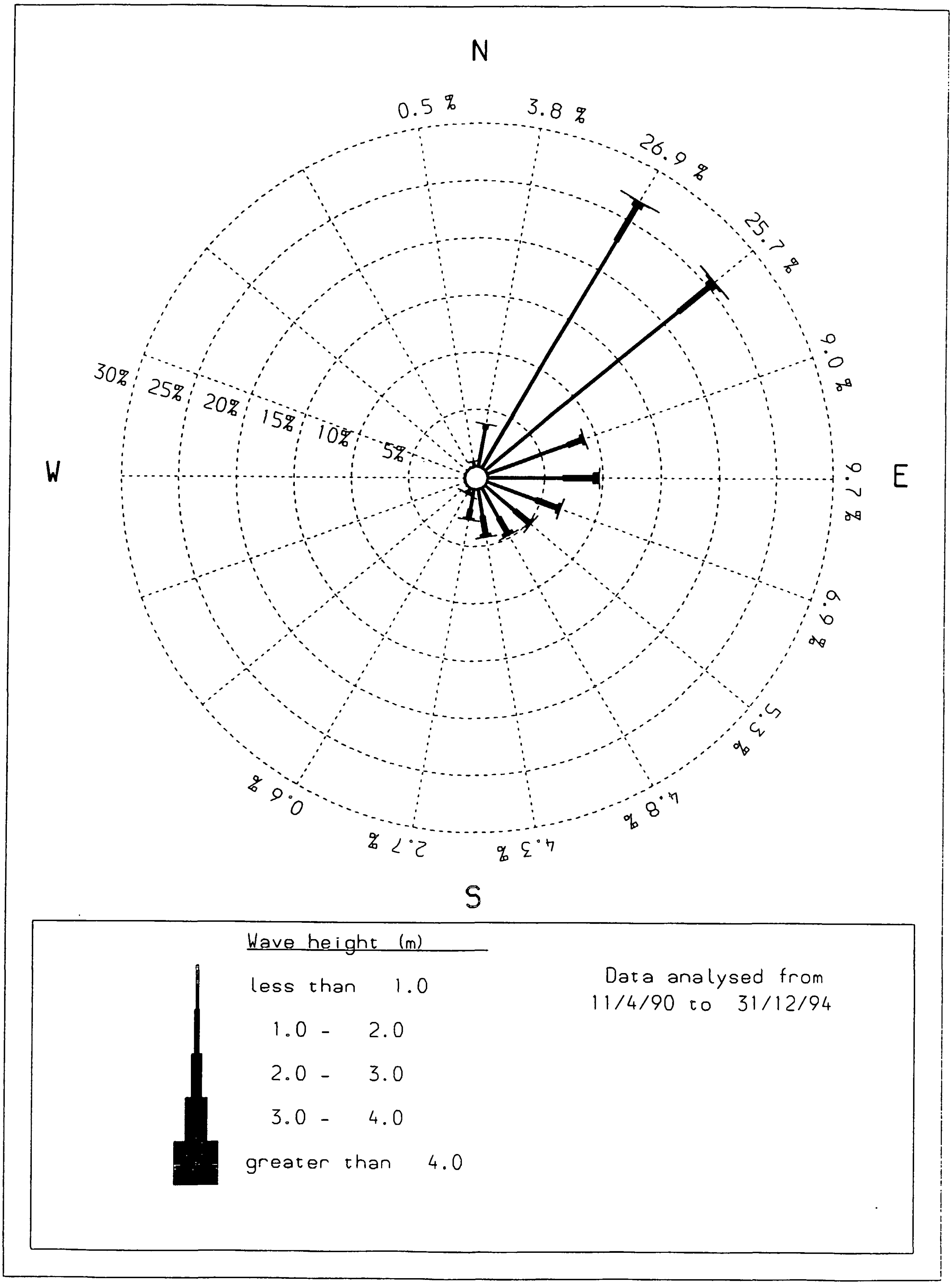
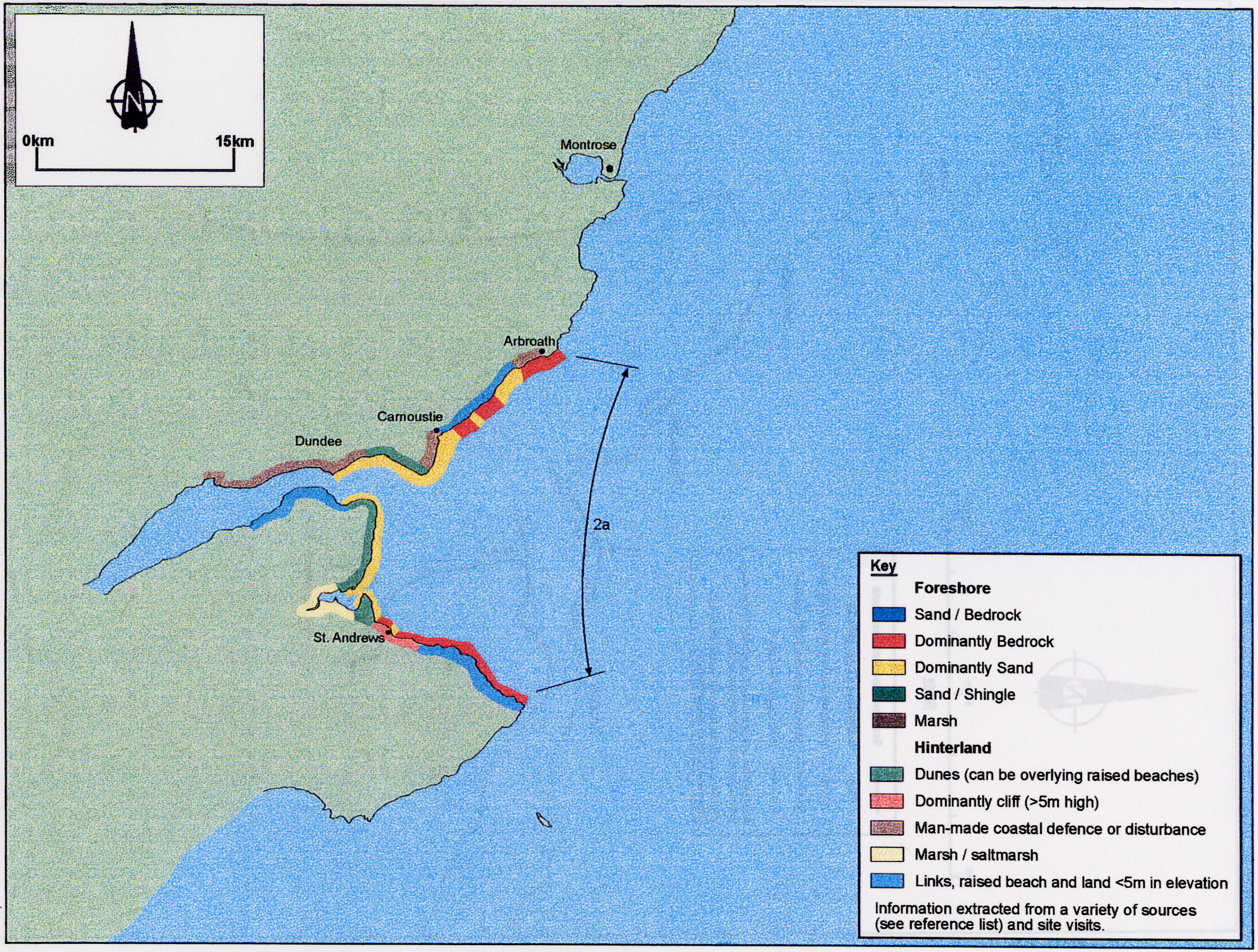


Figure 15 Offshore swell wave climate east of Aberdeen

Figure 16 Sub-cell 2a - Foreshore and hinterland characteristics



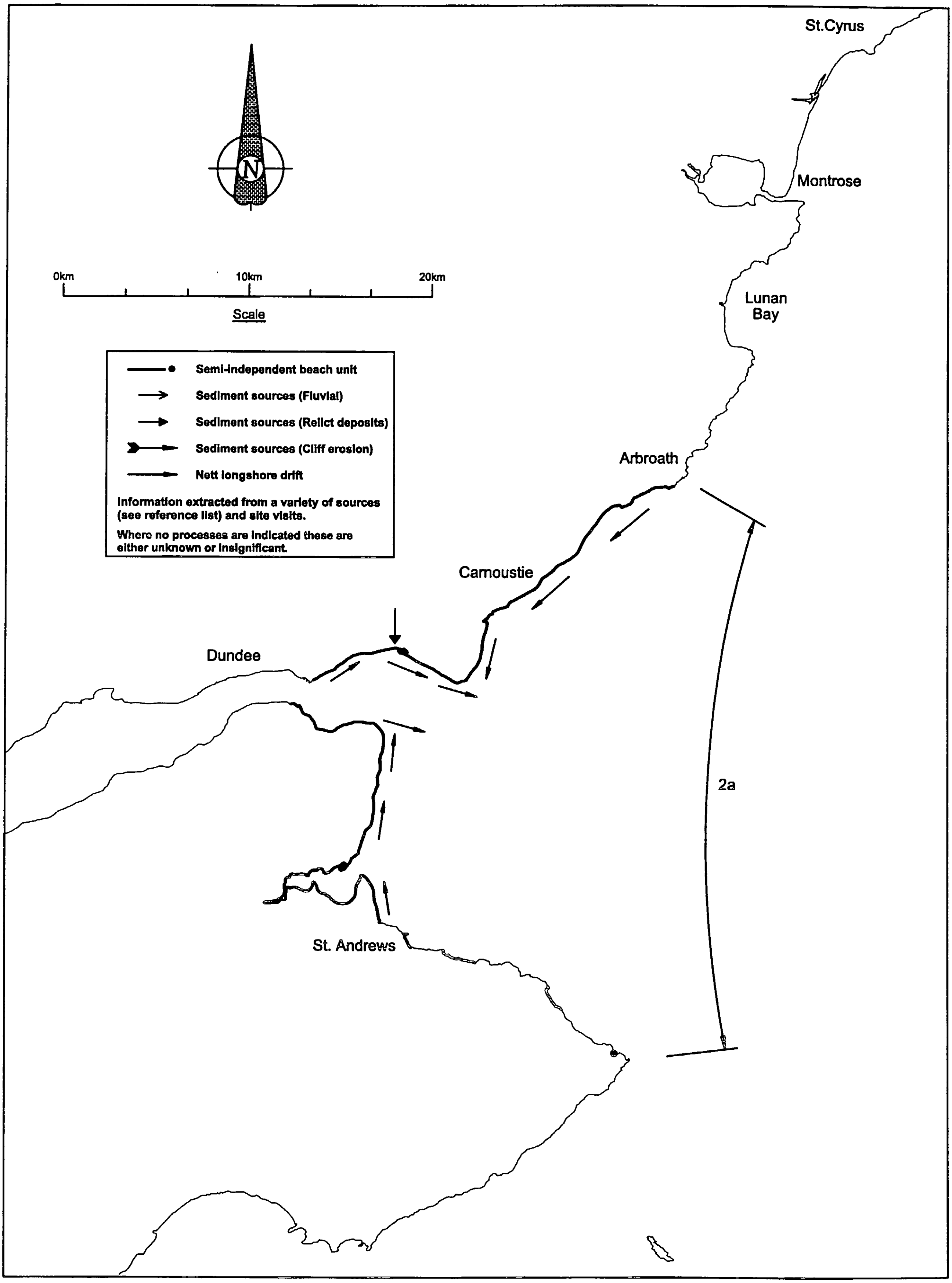
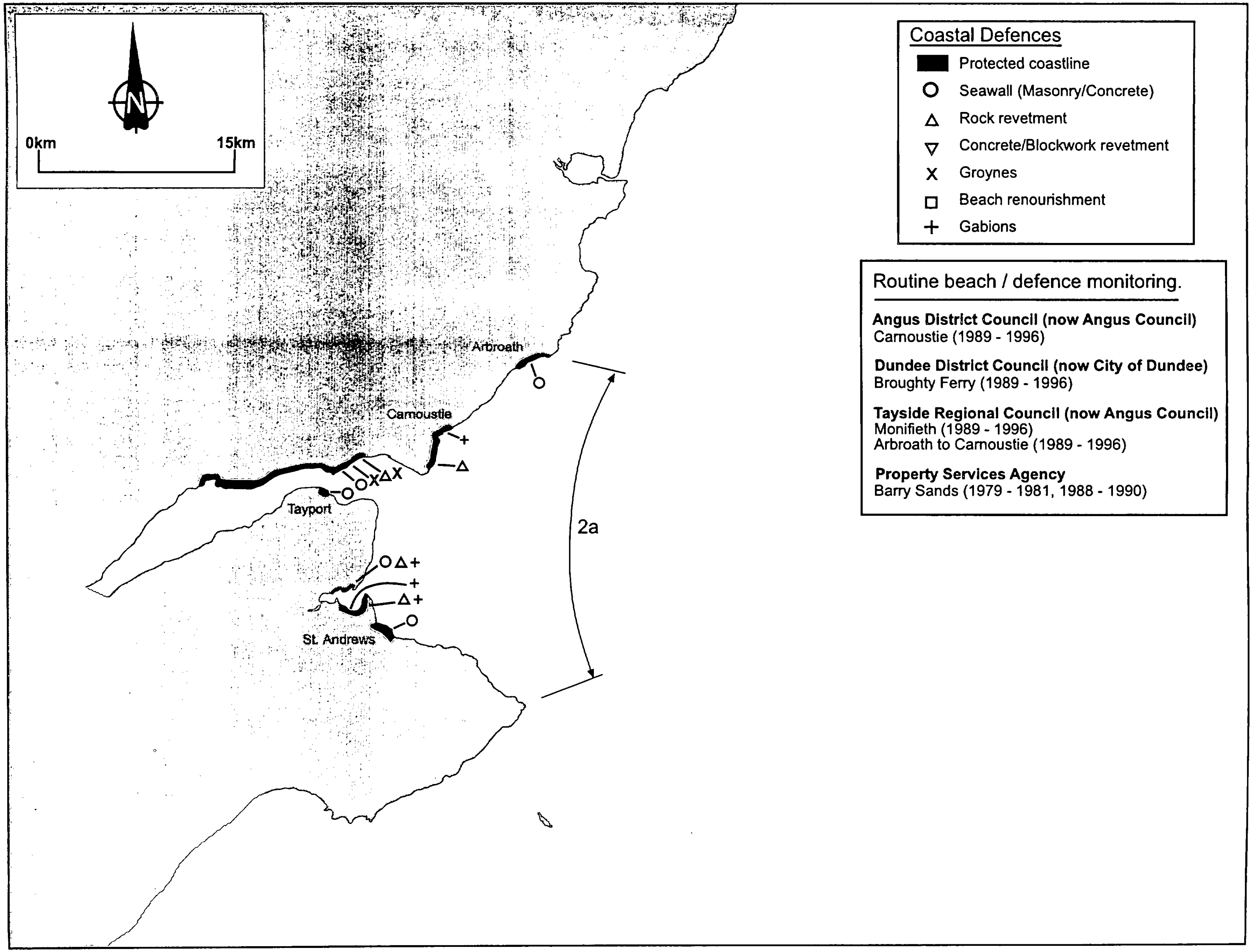


Figure 17 Sub-cell 2a - Dominant littoral processes

Figure 18 Sub-cell 2a - Coastal defences and monitoring



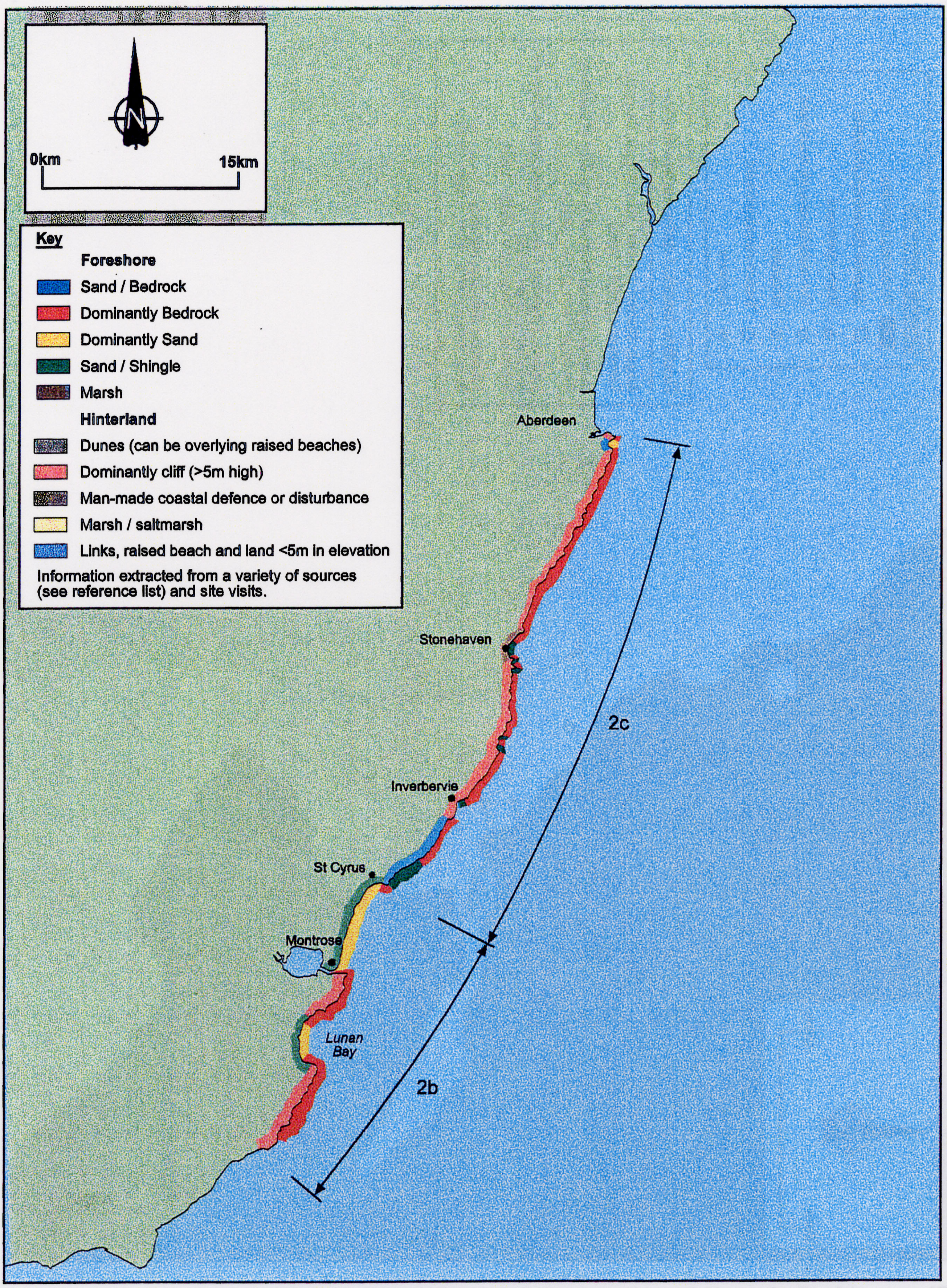


Figure 19 Sub-cells 2b & 2c - Foreshore and hinterland characteristics

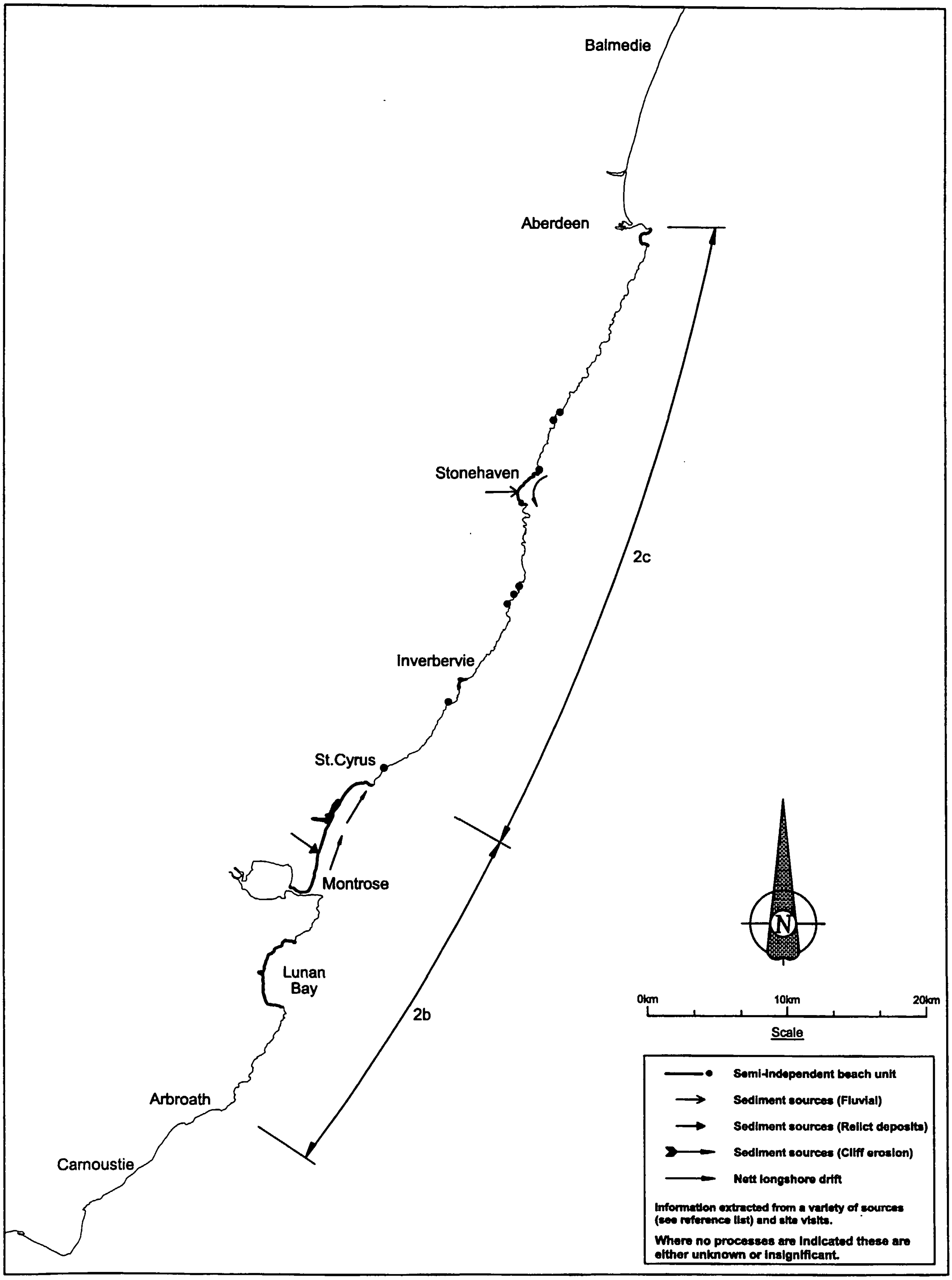


Figure 20 Sub-cells 2b & 2c - Dominant littoral processes

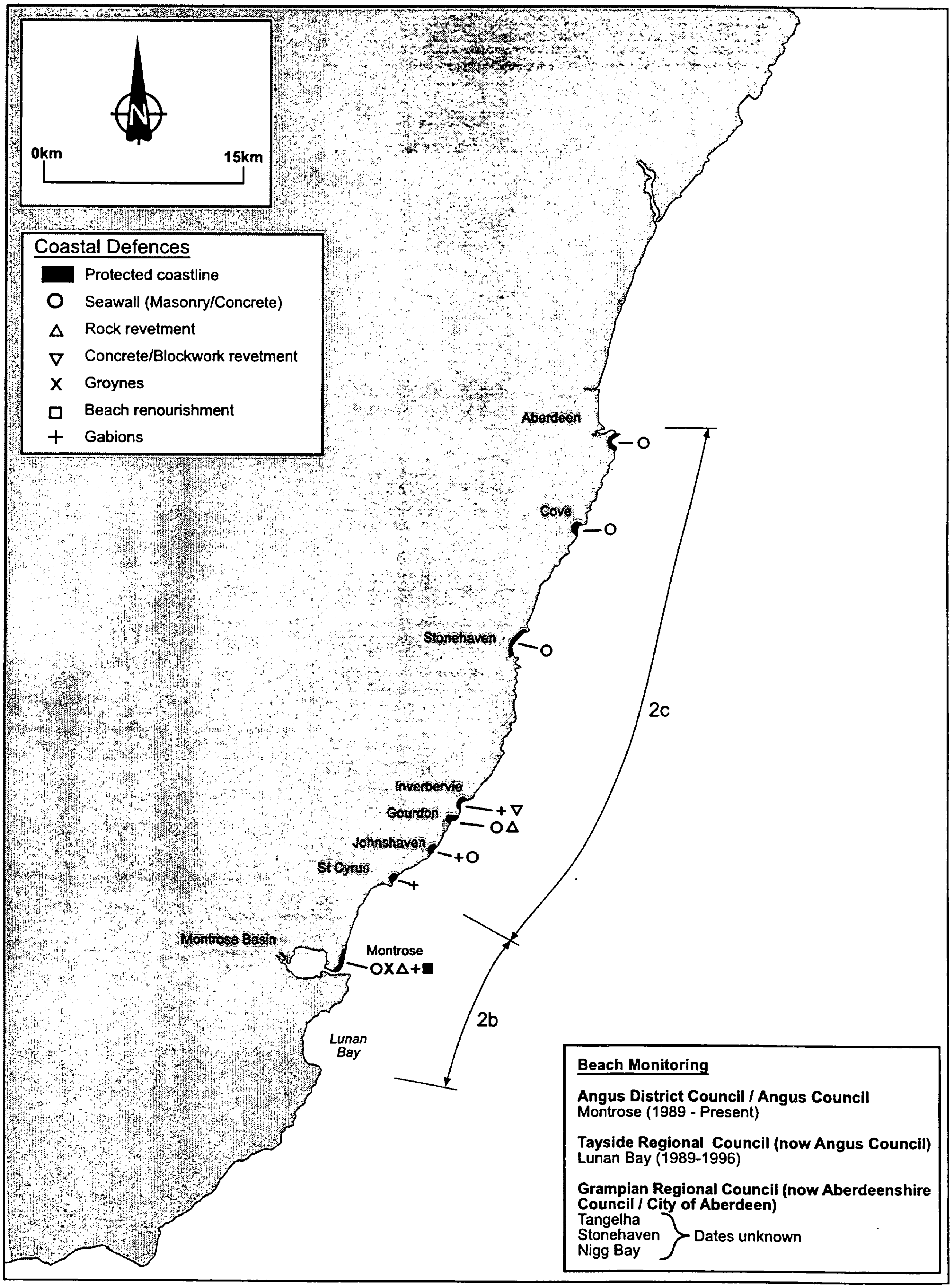


Figure 21 Sub-cells 2b & 2c - Coastal defences and monitoring

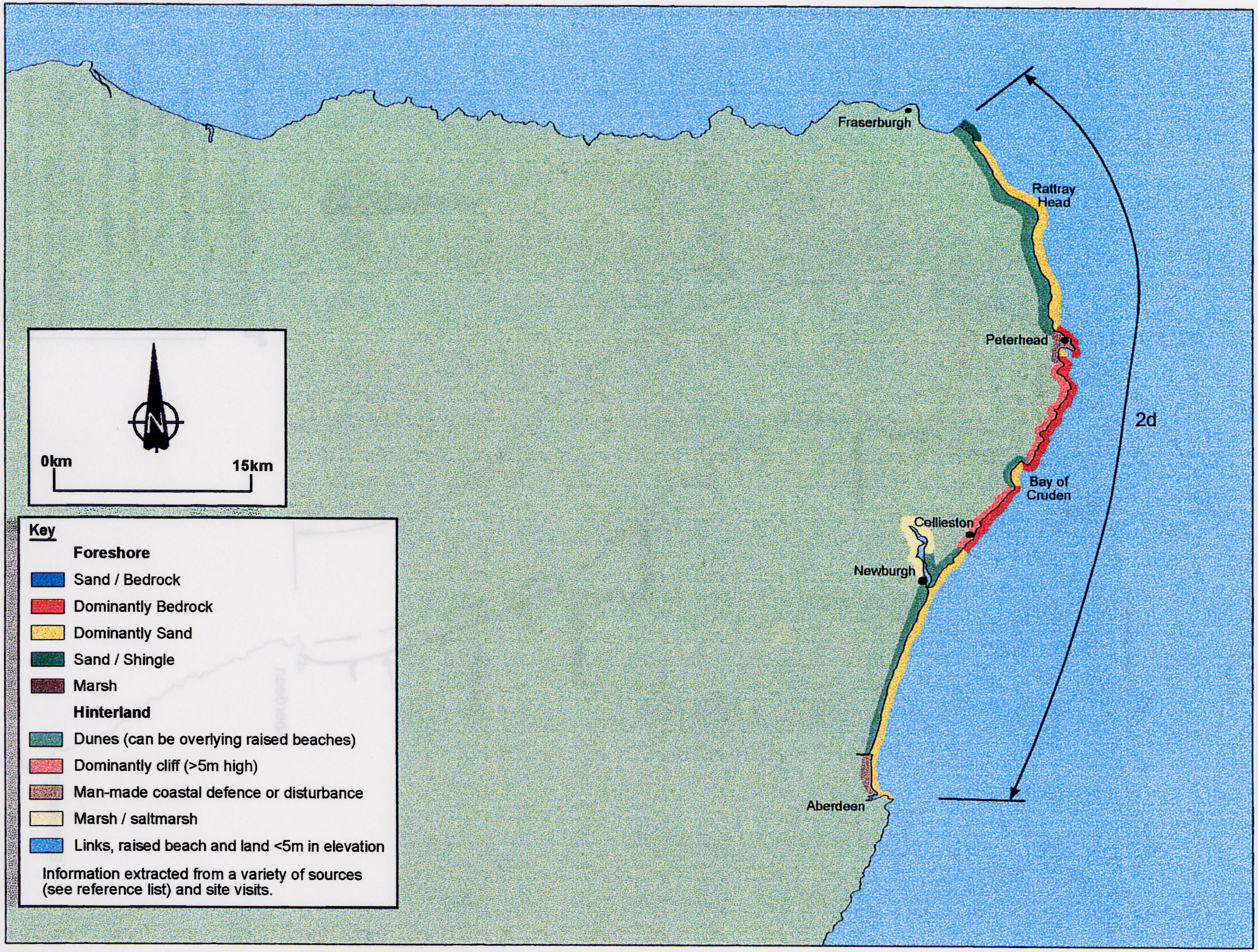


Figure 22 Sub-cell 2d - Foreshore and hinterland characteristics

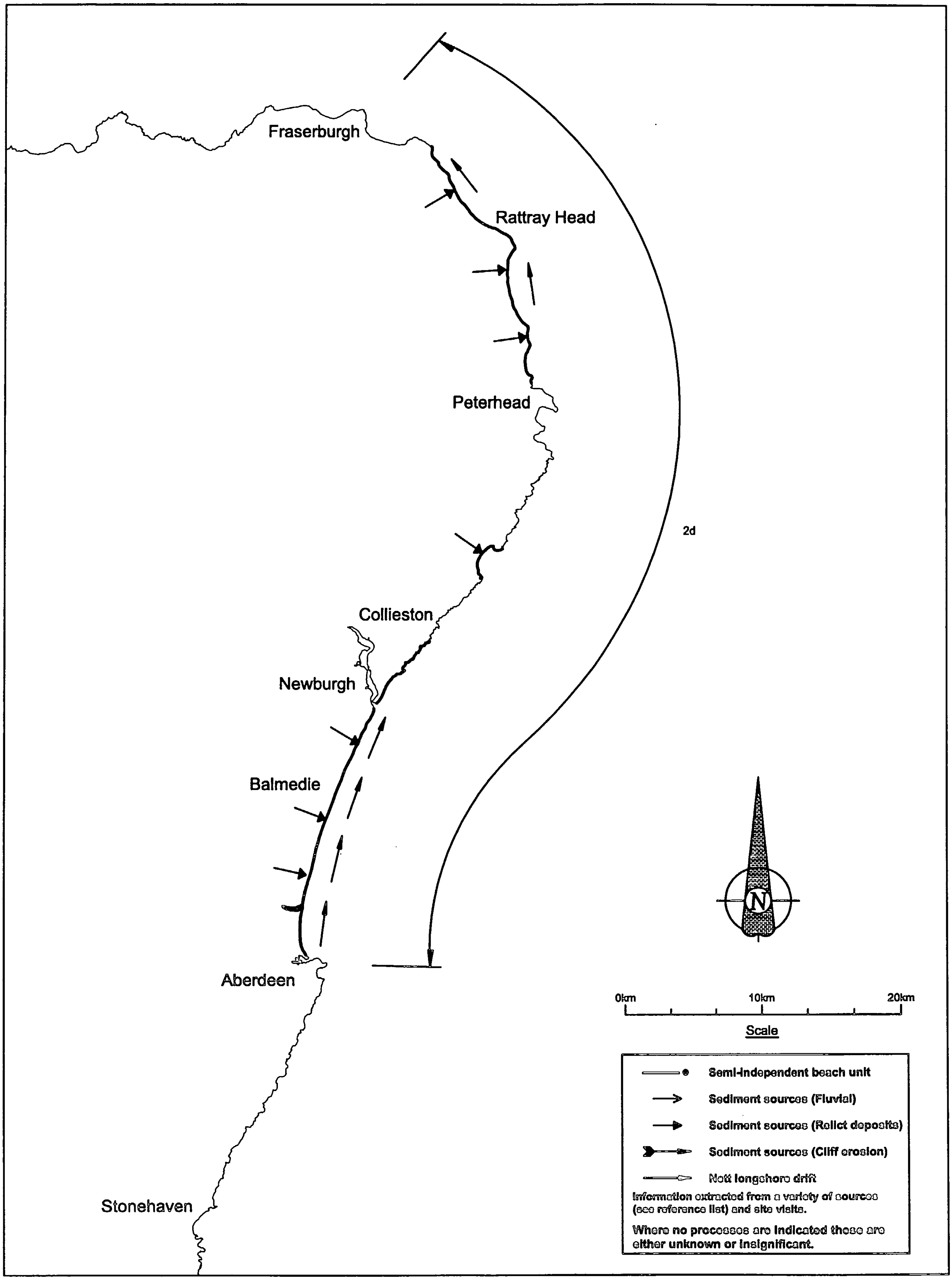
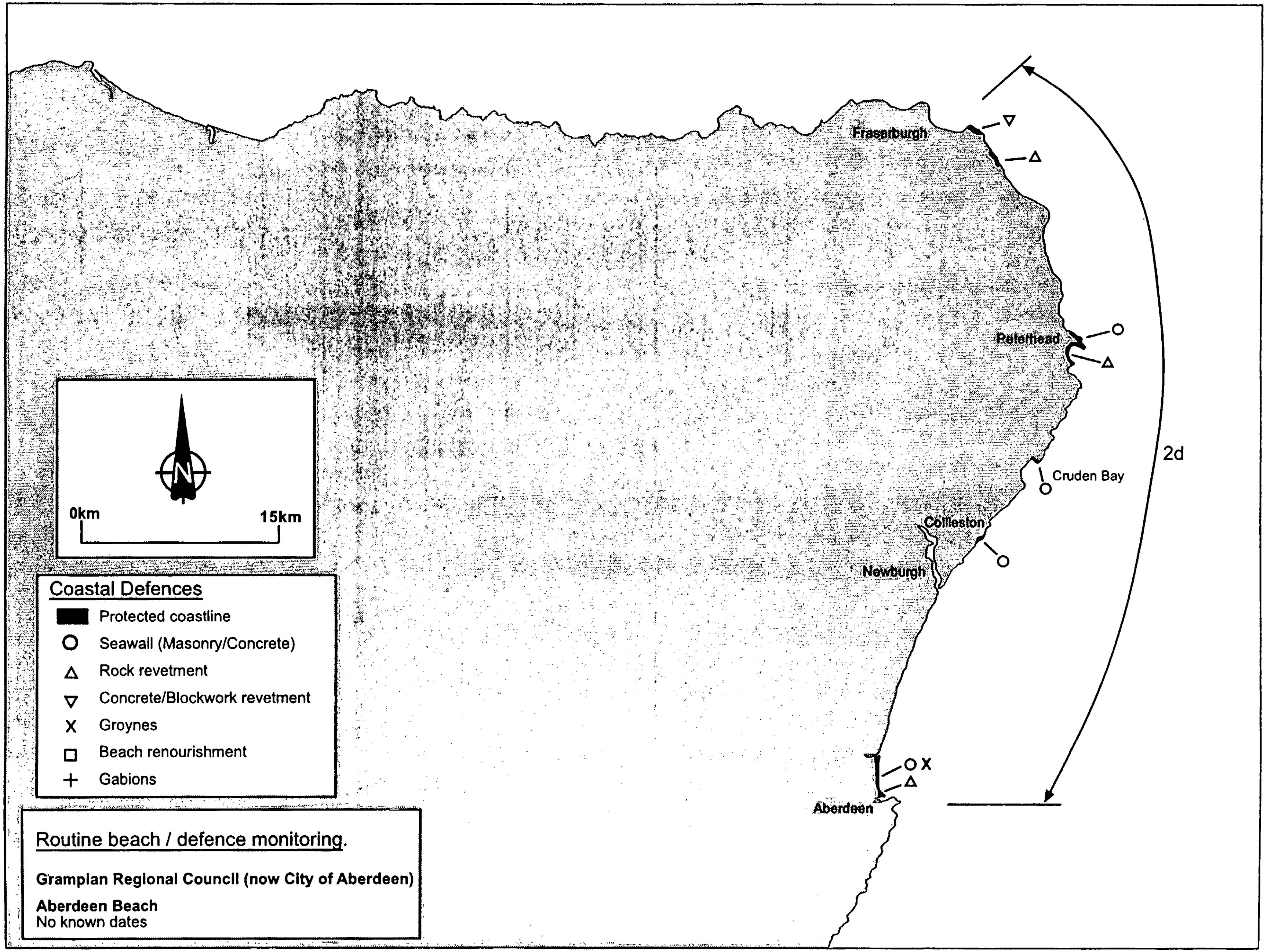


Figure 23 Sub-cell 2d - Dominant littoral processes

Figure 24 Sub-cell 2d - Coastal defences and monitoring



Appendix 1 Cell 2 - Details of Sites of Special Scientific Interest

Extracted from the British Oceanographic Data Centre's UKDMAP. Data correct to 1996.

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Fife Ness Coast	NO625107	116.9	1987	Geological interest Saltmarsh Vegetated shingle Dry grassland Woodland Fen
St Andrews-Craig Hartle	NO545152	133.4	1989	Geological interest Rocky shore Saltmarsh Sea cliff (hard rock) Dry grassland Maritime heath Woodland Fen Flush or seepage line Seabirds breeding Comments: wintering waders - Locally important
Eden Estuary	NO475195	1160.7	1990	Tidal flats Saltmarsh Sand dunes Woodland Fen Scarce or rare plants Terrestrial invertebrates Wildfowl breeding Site used for wintering wildfowl - Internationally important
Earlshall Muir	NO485220	431.9	1983	Sand dunes Woodland Terrestrial invertebrates
Tayport-Tentsmuir Coast	NO452294	1048.3	1984	Geomorphological interest Tidal flats Sand dunes Scarce or rare plants Terrestrial invertebrates Mammals noted Site used for wintering wildfowl - Nationally important
Balmerino-Wormit Shore	NO380257	85.2	1989	Geological interest
Flisk Wood	NO335236	63.4	1984	Woodland
Inner Tay Estuary	NO280220	5399.9	1985	Saltmarsh Phragmites reedbed Site used for wintering wildfowl - Internationally important
Carey	NO174170	1.7	1990	Geological interest

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Monifieth Bay	NO485313	212.7	1985	Site used for wintering wildfowl - Internationally important Comments: wintering waders - Nationally important
Barry Links	NO532319	1041.1	1985	Geomorphological interest Sand dunes Scarce or rare plants Lower plants Site used for wintering wildfowl - Locally important
Easthaven	NO588356	1.2	1989	Dry grassland Scarce or rare plants
Elliot Links	NO620390	28.7	1985	Botanical Entomological
Whiting Ness-Ethie Haven	NO670428	153	1989	Geological interest Sea cliff (hard rock) Dry grassland Scarce or rare plants Lower plants Terrestrial invertebrates Seabirds breeding Comments: wintering waders - Nationally important
Rickle Craig to Scurdie Ness	NO727545	73.1	1987	Geological interest Rocky shore Saltmarsh Dry grassland Marine biological interest Terrestrial invertebrates
Montrose Basin	NO685580	888.5	1986	Geological interest Tidal flats Fen Scarce or rare plants Lower plants Marine biological interest Site used for wintering wildfowl - Internationally important Comments: wintering waders - Nationally important
St Cyrus & Kinnaber Links	NO745630	311.8	1989	Biological Interest Plants
Findon Moor	NO745630	26.2	1985	Open water Dry grassland Maritime heath Flush or seepage line Lower plants
Milton Ness	NO769649	25.8	1990	Geological interest
Crawton Bay	NO879796	9.2	1990	Geological interest Sea cliff (hard rock)
Fowlsheugh	NO881799	7.6	1983	Sea cliff (hard rock) Seabirds breeding

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Garron Point	NO887874	59.8	1989	Geological interest Saltmarsh Sand dunes Vegetated shingle Terrestrial invertebrates
Cove	NJ954005	9.5	1983	Sea cliff (hard rock) Scarce or rare plants Terrestrial invertebrates Comments: Only British site for rare fern discovered in 1838
Nigg Bay	NJ966045	4.7	1984	Geological interest
Foveran Links	NK000225	203.2	1984	Geomorphological interest Sand dunes Wet grassland/grazing marsh Maritime heath Fen Comment: Migrant birds & moulting seabirds
Sands of Forvie & Ythan Estuary	NK020275	976.3	1984	Geomorphological interest Tidal flats Rocky shore Open water Saltmarsh Sand dunes Sea cliff (hard rock) Maritime heath Fen Flush or seepage line Phragmites reedbed Lower plants Terrestrial invertebrates Wildfowl breeding Seabirds breeding Site used for wintering wildfowl - Internationally important Comments: Part NNR
Collieston & Whinnyfold Coast	NK060310	104	1985	Geological interest Sea cliff (hard rock) Maritime heath Flush or seepage line Seabirds breeding
Bullers of Buchan Coast	NK110380	109	1984	Geological interest Sea cliff (hard rock) Maritime heath Peatland Flush or seepage line Seabirds breeding

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Loch of Strathbeg	NK075590	982.8	1985	Geomorphological interest Sand dunes Woodland Fen Phragmites reedbed Scarce or rare plants Terrestrial invertebrates Waders breeding Wildfowl breeding Seabirds breeding Site used for wintering wildfowl - Nationally important Site used by other wintering bird species Comments: 5% of NW wintering swans & geese
Cairnbulg to St Combs Coast	NK053641	55	1989	Geological interest

Appendix 2 Cell 2 - Location of known archaeological and historical sites within 500m of the coastline

Note: This map has not been published within the report but may be consulted (by prior arrangement) by contacting:

Earth Science Group
Advisory Services
Scottish Natural Heritage
2 Anderson Place
EDINBURGH
EH6 5NP

The underlying data are updated regularly by the National Monuments Record of Scotland and are available for inspection there, by prior arrangement.

Appendix 3 Useful addresses

Contact addresses for organisations referred to within the report and other useful contacts.

British Geological Survey (Scotland)
Murchison House
West Mains Road
Edinburgh — Tel: 0131-667 1000
EH9 3LA — Fax: 0131-668 2683

British Geological Survey (Coastal Geology Group)
Kingsley Dunham Centre
Keyworth
Nottingham — Tel: 0115 9363100
NG12 5GG — Fax: 0115 9363200

British Oceanographic Data Centre (BODC)
See Proudman Oceanographic Laboratory

Crown Estate Commission
10 Charlotte Square
Edinburgh — Tel: 0131-226 7241
EH2 4DR — Fax: 0131-220 1366

Historic Scotland
Longmore House
Salisbury Place
Edinburgh — Tel: 0131-668 8600
EH9 1SH — Fax: 0131-668 8789

HR Wallingford Ltd
Howbery Park
Wallingford
Oxon — Tel: 01491 835381
OX10 8BA — Fax: 01491 825539

Hydrographic Office (Taunton)
OCM (C)
Admiralty Way
Taunton
Somerset — Tel: 01823 337900
TA1 2DN — Fax: 01823 284077

Institute of Marine Studies
University of St Andrews
St Andrews
Fife — Tel: 01334 462886
KY16 9AJ — Fax: 01334 462921

Institute of Oceanographic Sciences
See Proudman Oceanographic Laboratory

Joint Nature Conservation Committee
Monkstone House
City Road
Peterborough
PE1 1JY
Tel: 01733 562626
Fax: 01733 555948

Macaulay Land Use Research Institute
Craigiebuckler
Aberdeen
AB9 2QL
Tel: 01224 318611
Fax: 01224 311556

Marine Information Advisory Service (MIAS)
See Proudman Oceanographic Laboratory

Metoc plc (Metocean)
Exchange House
Station Road
Liphook
Hampshire
GU30 7DW
Tel: 01428 727800
Fax: 01428 727122

Ministry of Agriculture, Fisheries and Food
(Flood and Coastal Defence Division)
Eastbury House
30-34 Albert Embankment
London
SE1 7TL
Tel: 0207 238 6742
Fax: 0207 238 6665

National Museums of Scotland
c/o Royal Museum of Scotland
Chambers Street
Edinburgh
EH1 1JF
Tel: 0131-225 7534
Fax: 0131-220 4819

Ordnance Survey (Scottish Region)
Grayfield House
5 Bankhead Avenue
Edinburgh
EH11 4AE
Tel: 0845 605 0505

Proudman Oceanographic Laboratory
(British Oceanographic Data Centre, MIAS & Permanent Service for Mean Sea Level)
Bidston Observatory
Birkenhead
Merseyside
L43 7RA
Tel: 0151-653 8633
Fax: 0151-653 6269

Permanent Service for Mean Sea Level (PSMSL)
See Proudman Oceanographic Laboratory

Royal Commission on the Ancient and Historical Monuments of Scotland (RCAHMS)
John Sinclair House
16 Bernard Terrace
Edinburgh
EH8 9NX
Tel: 0131-662 1456
Fax: 0131-662 1477

Scottish Environment Protection Agency
Erskine Court
The Castle Business Park
Stirling
FK9 4TR
Tel: 01786 457700
Fax: 01786 446885

Scottish Executive (re Coast Protection Act (CPA))
Rural Affairs Department
European Environment and Engineering Unit
Victoria Quay
Edinburgh
EH6 6QQ
Tel: 0131-556 8400

Scottish Executive (re Food and Environment Protection Act (FEPA))
Rural Affairs Department
Pentland House
47 Robbs Loan
Edinburgh
EH14 1TY
Tel: 0131-556 8400

Scottish Executive
Marine Laboratory
PO Box 101
Victoria Road
Torry
Aberdeen
Tel: 01224 876544
Fax: 01224 295511

Scottish Natural Heritage
12 Hope Terrace
Edinburgh
EH9 2AS
Tel: 0131-447 4784
Fax: 0131-446 2277

Scottish Trust for Underwater Archaeology
c/o Department of Archaeology
University of Edinburgh
16-20 George Square
Edinburgh
EH8 9JZ
Tel: 0131-650 2368
Fax: 0131-650 4094

Scottish Tourist Board
23 Ravelston Terrace
Edinburgh
EH4 3EU
Tel: 0131-332 2433
Fax: 0131-343 1513

UK Meteorological Office
Marine Consulting Service
Johnstone House
London Road
Bracknell Tel: 01344 420242
RG12 2UR Fax: 01344 854412

UK Offshore Operators Association Ltd (UKOOA)
30 Buckingham Gate
London Tel: 020 7802 2400
SW1E 6NN Fax: 020 7802 2401

Appendix 4 Glossary

Abrasion platform	A rock or clay platform which has been worn by the processes of abrasion (i.e. frictional erosion by material transported by wind and waves)
Accretion	The accumulation of (beach) sediment, deposited by natural fluid flow processes
A Class tide gauge	One of a UK network maintained to the highest and most consistent standards
Amplitude	Half of the peak-to-trough range (or height)
Apron	Layer of stone, concrete or other material to protect the toe of a seawall
Armour layer	Protective layer on a breakwater or seawall composed of **armour units**
Armour unit	Large quarried stone or specially shaped concrete block used as primary protection against wave action
Asperities	The three-dimensional irregularities forming the surface of an irregular stone (or rock) subject to wear and rounding during attraction
Astronomical tide	The tidal levels and character which would result from gravitational effects, e.g. of the Earth, Sun and Moon, without any atmospheric influences
Back-rush	The seaward return of water following the **up-rush** of a wave
Backshore	The upper part of the active beach above the normal reach of the tides (high water), but affected by large waves occurring during a high tide
Barrier beach	A sand or shingle bar above high tide, parallel to the coastline and separated from it by a lagoon
Bathymetry	Refers to the spatial variability of levels on the seabed
Beach	A deposit of non-cohesive material (e.g. sand, gravel) situated on the interface between dry land and the sea (or other large expanse of water) and actively "worked" by present-day hydrodynamic processes (i.e. waves, tides and currents) and sometimes by winds
Beach crest	The point representing the limit of high tide storm wave **run-up**
Beach face	From the **beach crest** out to the limit of sediment movement
Beach head	The cliff, dune or seawall forming the landward limit of the active beach
Beach plan shape	The shape of the beach in plan; usually shown as a contour line, combination of contour lines or recognizable features such as beach crest and/or still water line
Beach profile	A cross-section taken perpendicular to a given beach contour; the profile may include the face of a dune or seawall, extend over the **backshore**, across the **foreshore**, and seaward underwater into the **nearshore** zone
Beach recharge	Supplementing the natural volume of sediment on a beach, using material from elsewhere - also known as beach replenishment/nourishment/feeding

Bed forms	Features on a seabed (e.g. ripples and sand waves) resulting from the movement of sediment over it
Bed load	Sediment transport mode in which individual particles either roll or slide along the seabed as a shallow, mobile layer a few particle diameters deep
Bed shear stress	The way in which waves (or currents) transfer energy to the sea bed
Benefits	The economic value of a scheme, usually measured in terms of the cost of damages avoided by the scheme, or the valuation of perceived amenity or environmental improvements
Berm	(1) On a beach: a nearly horizontal plateau on the **beach face** or **backshore**, formed by the deposition of beach material by wave action or by means of a mechanical plant as part of a **beach recharge** scheme (2) On a structure: a nearly horizontal area, often built to support or key-in an **armour layer**
Boulder	A rounded rock on a beach, greater than 250mm in diameter, larger than a **cobble** - see also **gravel, shingle**
Boundary conditions	Environmental conditions, e.g. waves, currents, drifts, etc. used as boundary input to physical or numerical models
Bound long wave	Long wave directly due to the variation in set-down at the breaker line due to wave groups
Breaching	Failure of the **beach head** allowing flooding by tidal action
Breaker depth	Depth of water, relative to **still water level** at which waves break; also known as **breaking depth** or limiting depth
Breaker index	Maximum ratio of **wave height** to water depth in the surf zone
Breaker zone	The zone within which waves approaching the coastline commence breaking, typically in water depths of between 5 and 10 metres
Breaking	Reduction in wave energy and height in the surf zone due to limited water depth
Breastwork	Vertically-faced or steeply inclined structure usually built with timber and parallel to the shoreline, at or near the **beach crest**, to resist erosion or mitigate against flooding
Bypassing	Moving beach material from the **updrift** to the **downdrift** side of an obstruction to **longshore-drift**
Chart datum	The level to which both tidal levels and water depths are reduced - on most UK charts, this level is that of the predicted lowest **astronomical tide** level (LAT)
Clay	A fine grained, plastic, sediment with a typical grain size less than 0.004mm. Possesses electro-magnetic properties which bind the grains together to give a bulk strength or cohesion
Climate change	Refers to any long-term trend in mean sea level, **wave height**, wind speed, drift rate etc.
Closure depth	The depth at the offshore limit of discernible bathymetric change between surveys.
Coastal cell	See Sediment cell

Coastal defence	General term used to encompass both coast protection against erosion and sea defence against flooding
Coastal forcing	The natural processes which drive coastal hydro- and morpho-dynamics (e.g. winds, waves, tides, etc)
Coastal processes	Collective term covering the action of natural forces on the shoreline, and nearshore seabed
Coastal zone	Some combination of land and sea area, delimited by taking account of one or more elements
Coast protection	Protection of the land from erosion and encroachment by the sea
Cobble	A rounded rock on a beach, with diameter ranging from about 75 to 250mm - see also **boulder, gravel, shingle**
Cohesive sediment	Sediment containing significant proportion of clays, the electromagnetic properties of which cause the sediment to bind together
Conservation	The protection of an area, or particular element within an area, whilst accepting the dynamic nature of the environment and therefore allowing change
Core	(1) A cylindrical sample extracted from a beach or seabed to investigate the types and depths of sediment layers (2) An inner, often much less permeable portion of a breakwater, or barrier beach
Coriolis	Force due to the Earth's rotation, capable of generating currents
Crest	Highest point on a beach face, breakwater or seawall
Cross-shore	Perpendicular to the shoreline
Current	Flow of water
Current-refraction	Process by which wave velocity is affected by a current
Cusp	Seaward bulge, approximately parabolic in shape, in the beach contours. May occur singly, in the lee of an offshore bulk or island, or as one of a number of similar, approximately regularly-spaced features on a long straight beach
Deep water	Water too deep for waves to be affected by the seabed; typically taken as half the **wavelength**, or greater
Deflation	Erosion of dunes by wind action
Depth-limited	Situation in which wave generation (or **wave height**) is limited by water depth
Design wave condition	Usually an extreme wave condition with a specified return period used in the design of coastal works
Detached breakwater	A breakwater without any constructed connection to the shore
Diffraction	Process affecting wave propagation, by which wave energy is radiated normal to the direction of wave propagation into the lee of an island or breakwater
Diffraction coefficient	Ratio of diffracted **wave height** to deep water **wave height**
Diurnal	Literally `of the day', but here meaning having a period of a `tidal day', i.e. about 24.8 hours

Downdrift	In the direction of the nett longshore transport of beach material
Drying beach	That part of the beach which is uncovered by water (e.g. at low tide). Sometimes referred to as `subaerial' beach
Dunes	(1) Accumulations of windblown sand on the **backshore**, usually in the form of small hills or ridges, stabilised by vegetation or control structures (2) A type of bed form indicating significant sediment transport over a sandy seabed
Duration	The length of time a wind blows at a particular speed and from the same direction during the generation of storm waves
Ebb	Period when tide level is falling; often taken to mean the **ebb current** which occurs during this period
Edge waves	Waves which mainly exist shoreward of the breaker line, and propagate along the shore. They are generated by the incident waves, their amplitude is a maximum at the shoreline and diminishes rapidly in a seaward direction
Epifauna	Animals living in the sediment surface or on the surface of other plants or animals
Event	An occurrence meeting specified conditions, e.g. damage, a threshold **wave height** or a threshold water level
Exponential distribution	A model probability distribution
Extreme	The value expected to be exceeded once, on average, in a given (long) period of time
Fetch	Distance over which a wind acts to produce waves - also termed **fetch length**.
Fetch-limited	Situation in which wave energy (or **wave height**) is limited by the size of the wave generation area (**fetch**)
Forecasting	Prediction of conditions expected to occur in the near future, up to about two days ahead
Foreshore	The intertidal area below highest tide level and above lowest tide level
Freeboard	The height of the crest of a structure above the **still water level**
Friction	Process by which energy is lost through shear stress
Friction factor	Factor used to represent the roughness of the sea bed
Frontager	Person or persons owning, and often living in, property immediately landward of the beach
Fully-developed sea	A wave condition which cannot grow further without an increase in wind speed - also fully-arisen sea
GIS	Geographical Information System. A database of information which is geographically orientated, usually with an associated visualization system
Gravel	Beach material, coarser than sand but finer than **pebbles** (2-4mm diameter)
Group velocity	The speed of wave energy propagation. Half the wave **phase velocity** in **deep water**, but virtually the same in **shallow water**

Groyne	Narrow, roughly shore-normal structure built to reduce longshore currents, and/ or to trap and retain beach material. Most groynes are of timber or rock, and extend from a seawall, or the **backshore**, well onto the **foreshore** and rarely even further offshore. In the USA and historically called a **groin**
Groyne bay	The beach compartment between two **groynes**
Gumbel distribution	A model probability distribution, commonly used in wind and water level analysis
Hard defences	General term applied to impermeable coastal defence structures of concrete, timber, steel, masonry etc, which reflect a high proportion of incident wave energy, cf **soft defences**
Hindcasting	In wave prediction, the retrospective forecasting of waves using measured wind information
Historic event analysis	Extreme analysis based on hindcasting typically ten events over a period of 100 years
Incident wave	Wave moving landward
Infauna	Animals living in the sediment
Infragravity waves	Waves with periods above about 30 seconds generated by wave groups breaking in the surf zone
Inshore	Areas where waves are transformed by interaction with the sea bed
Intertidal	The zone between the high and low water marks
Isobath	Line connecting points of equal depth, a seabed contour
Isopachyte	Line connecting points on the seabed with an equal depth of sediment
Joint probability	The probability of two (or more) things occurring together
Joint probability density	Function specifying the joint distribution of two (or more) variables
Joint return period	Average period of time between occurrences of a given joint probability event
JONSWAP spectrum	Wave spectrum typical of growing deep water waves
Limit of storm erosion	A position, typically a maximum water depth of 8 to 10 metres, often identifiable on surveys by a break (i.e. sudden change) in slope of the bed
Littoral	Of or pertaining to the shore
Littoral drift, Littoral transport	The movement of **beach material** in the **littoral zone** by waves and currents. Includes movement parallel (longshore drift) and perpendicular (cross-shore transport) to the shore
Locally generated waves	Waves generated within the immediate vicinity, say within 50km, of the point of interest
Log-normal distribution	A model probability distribution
Long-crested random waves	Random waves with variable heights and periods but a single direction
Longshore	Parallel and close to the coastline
Longshore bar	Bar running approximately parallel to the shoreline

Longshore drift	Movement of (beach) sediments approximately parallel to the coastline
Long waves	Waves with periods above about 30 seconds generated by wave groups breaking in the surf zone
Macro-tidal	Tidal range greater than 4m
Managed landward realignment	The deliberate setting back of the existing line of defence in order to obtain engineering and/or environmental advantages - also referred to as managed retreat
Marginal probability	The probability of a single variable in the context of a joint probability analysis
Marginal return period	The return period of a single variable in the context of a joint probability analysis
Meso-tidal	Tidal range between 2m and 4m
Micro-tidal	Tidal range less than 2m
Morphologically averaged wave condition	A single wave condition producing the same nett longshore drift as a given proportion of the annual wave climate
Mud flat	An area of fine silt usually exposed at low tide but covered at high tide, occurring in sheltered estuaries or behind shingle bars or sand spits
Nearshore	The zone which extends from the **swash zone** to the position marking the start of the **offshore zone**, typically at water depths of the order of 20m
Ness	Roughly triangular promontory of land jutting into the sea, often consisting of mobile material, i.e. a beach form
Numerical modelling	Refers to analysis of coastal processes using computational models
Offshore	The zone beyond the **nearshore zone** where sediment motion induced by waves alone effectively ceases and where the influence of the sea bed on wave action is small in comparison with the effect of wind
Operational	The construction, maintenance and day-to-day activities, associated with beach management
Overtopping	Water carried over the top of a **coastal defence** due to wave **run-up** exceeding the **crest** height
Overwash	The effect of waves **overtopping** a **coastal defence**, often carrying sediment landwards which is then lost to the beach system
Peaks over threshold (POT)	Refers to the maximum value of a variable during each excursion above a threshold value
Pebbles	Beach material usually well-rounded and between about 4mm to 75mm diameter
Persistence of storms	The duration of sea states above some severity threshold (e.g. **wave height**)
Phase velocity	The velocity at which a wave crest propagates, cf **group velocity**
Physical modelling	Refers to the investigation of coastal processes using a scaled model

Pierson-Moskowitz spectrum	Wave spectrum typical of fully-developed deep water waves
Piezometric surface	The level within (or above) a soil stratum at which the pore-pressure is zero
Pocket Beach	A beach, usually small, between two **headlands**
Preservation	Static protection of an area or element, attempting to perpetuate the existence of a given `state'
Probability density function	Function specifying the distribution of a variable
Profile of storms	Refers to the persistence of storms coupled with the rate of change of sea state (e.g. **wave height**) within the storms
Reef	A ridge of rock or other material lying just below the surface of the sea
Reflected wave	That part of an incident wave that is returned (reflected) seaward when a wave impinges on a **beach**, **seawall** or other reflecting surface
Refraction coefficient	Ratio of refracted **wave height** to deep water **wave height**
Refraction (of water waves)	The process by which the direction of a wave moving in **shallow water** at an angle to the contours is changed so that the wave crests tend to become more aligned with those contours
Regular waves	Waves with a single height, period and direction
Residual (water level)	The components of water level not attributable to astronomical effects
Return period	Average period of time between occurrences of a given event
Revetment	A sloping surface of stone, concrete or other material used to protect an embankment, natural coast or shoreline against erosion
Rip current	Jet-like seaward-going current normal to the shoreline associated with wave-induced longshore currents
Risk analysis	Assessment of the total risk due to all possible environmental inputs and all possible mechanisms
Runnel	Channels on a beach, usually running approximately shore-parallel and separated by beach ridges
Run-up, run-down	The upper and lower levels reached by a wave on a beach or coastal structure, relative to **still-water level**
Salient	Coastal formation of beach material developed by wave refraction and diffraction and longshore drift comprising of a bulge in the coastline towards an offshore island or breakwater, but not connected to it as in the case of a **tombolo** - see also **ness, cusp**
Sand	Sediment particles, mainly of quartz, with a diameter of between 0.062mm and 2mm, generally classified as fine, medium, coarse or very coarse
Scatter diagram	A two-dimensional histogram showing the joint probability density of two variables within a data sample
Sea defences	Works to alleviate flooding by the sea
Sea level rise	The long-term trend in mean sea level

Seawall	Solid coastal defence structure built parallel to the coastline
Sediment	Particulate matter derived from rock, minerals or bioclastic debris
Sediment cell	In the context of a strategic approach to coastal management, a length of coastline in which interruptions to the movement of sand or shingle along the beaches or nearshore sea bed do not significantly affect beaches in the adjacent lengths of coastline. Also referred to as a coastal cell
Sediment sink	Point or area at which beach material is irretrievably lost from a coastal cell, such as an estuary, or a deep channel in the seabed
Sediment source	Point or area on a coast from which beach material arises, such as an eroding cliff, or river mouth
Seiche	Standing wave oscillation in an effectively closed body of water
Semi-diurnal	Having a period of half a tidal day, i.e. 12.4 hours
Sequencing of storms	Refers to the temporal distribution of storms and therefore how they are grouped
Shallow water	Water of such depth that surface waves are noticeably affected by bottom topography. Typically this implies a water depth equivalent to less than half the **wave length**
Shingle	A loose term for coarse beach material, a mixture of gravel, pebbles and larger material, often well-rounded and of hard rock, e.g. chert, flint etc.
Shoaling	Decrease in water depth. The transformation of wave profile as they propagate inshore
Shoaling coefficient	Ratio of shoaled **wave height** to deep water **wave height**
Shoreline	One characteristic of the coast. Poorly defined but essentially the interface between land and sea
Shoreline management	The development of strategic, long-term and sustainable coastal defence policy within a **sediment cell**
Shore normal	A line at right-angles to the contours in the surf zone
Short-crested random waves	Random waves with variable heights, periods and directions
Significant wave height	The average height of the highest one third of the waves in a given sea state
Silt	Sediment particles with a grain size between 0.004mm and 0.062mm, i.e. coarser than **clay particles** but finer than **sand**
Soft defences	Usually refers to **beaches** (natural or designed) but may also relate to energy-absorbing beach-control structures, including those constructed of rock, where these are used to control or redirect **coastal processes** rather than opposing or preventing them
Spit	A long narrow accumulation of sand or shingle, lying generally in line with the coast, with one end attached to the land the other projecting into the sea or across the mouth of an estuary - see also **ness**

Standard of service	The adequacy of defence measured in terms of the return period (years) of the event which causes a critical condition (e.g. breaching, overtopping) to be reached
Still-water level (SWL)	Water level that would exist in the absence of waves
Strand line	An accumulation of debris (e.g. seaweed, driftwood and litter) cast up onto a beach, and lying along the limit of wave uprush
Sub-tidal beach	The part of the beach (where it exists) which extends from low water out to the approximate limit of storm erosion. The latter is typically located at a maximum water depth of 8 to 10 metres and is often identifiable on surveys by a break in the slope of the bed
Surf beat	Independent long wave caused by reflection of **bound long wave**
Surf zone	The zone of wave action extending from the water line (which varies with tide, surge, set-up, etc.) out to the most seaward point of the zone (**breaker zone**) at which waves approaching the coastline commence breaking, typically in water depths of between 5 to 10 metres
Surge	Changes in water level as a result of meteorological forcing (wind, high or low barometric pressure) causing a difference between the recorded water level and that predicted using harmonic analysis, may be positive or negative
Suspended load	A mode of sediment transport in which the particles are supported, and carried along by the fluid
Swash zone	The zone of wave action on the beach, which moves as water levels vary, extending from the limit of **run-down** to the limit of **run-up**
Swell (waves)	Remotely wind-generated waves. Swell characteristically exhibits a more regular and longer period and has longer crests than locally generated waves
Threshold of motion	The point at which the forces imposed on a sediment particle overcome its inertia and it starts to move
Tidal current	The movement of water associated with the rise and fall of the tides
Tidal range	Vertical difference in high and low water level once decoupled from the water level **residuals**
Tidal wave	The rise and fall in water level due to the passage of the tide
Tide	The periodic rise and fall in the level of the water in oceans and seas; the result of gravitational attraction of the sun and moon
Tides	(1) Highest astronomical tide (HAT), lowest astronomical tide (LAT): the highest and lowest levels, respectively, which can be predicted to occur under average meteorological conditions. These levels will not be reached every year. HAT and LAT are not the extreme levels which can be reached, as storm surges may cause considerably higher and lower levels to occur.

(2) Mean high water springs (MHWS), mean low water springs (MLWS): the height of mean high water springs is the average throughout a year of the heights of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is greatest. The height of mean low water springs is the average height obtained by the two successive low waters during the same periods.

(3) Mean high water neaps (MHWN), mean low water neaps (MLWN): the height of mean high water neaps is the average of the heights throughout the year of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is least. The height of mean low water neaps is the average height obtained by the two successive low waters during the same periods.

(4) Mean high water (MHW), mean low water (MLW): for the purpose of this manual, mean high/low water, as shown on Ordnance Survey Maps, is defined as the arithmetic mean of the published values of mean high/low water springs and mean high/low water neaps. This ruling applies to England and Wales. In Scotland the tidal marks shown on Ordnance Survey maps are those of mean high (or low) water springs (MH (or L) WS).

TMA spectrum — Wave spectrum typical of growing seas in limited water depths

Tombolo — Coastal formation of beach material developed by **refraction, diffraction** and **longshore drift** to form a `neck' connecting a coast to an offshore island or breakwater (see also **salient**)

Updrift — The direction opposite to that of the predominant longshore movement of beach material

Up-rush — The landward return of water following the **back-rush** of a wave

Water depth — Distance between the seabed and the **still water level**

Water level — Elevation of **still water level** relative to some datum

Wave celerity — The speed of wave propagation

Wave climate — The seasonal and annual distribution of **wave height, period** and **direction**

Wave climate atlas — Series of maps showing the variability of wave conditions over a long coastline

Wave direction — Mean direction of wave energy propagation relative to true North

Wave directional spectrum — Distribution of wave energy as a function of wave **frequency** and **direction**

Wave frequency — The inverse of **wave period**

Wave frequency spectrum — Distribution of wave energy as a function of frequency

Wave generation — Growth of wave energy by wind

Wave height	The vertical distance between the trough and the following crest
Wavelength	Straightline distance between two successive wave crests
Wave peak frequency	The inverse of wave peak period
Wave peak period	Wave period at which the spectral energy density is a maximum
Wave period	The time taken for two successive wave crests to pass the same point
Wave rose	Diagram showing the long-term distribution of **wave height** and direction
Wave set-up	Elevation of the water level at the coastline caused by radiation stress gradients in the surf zone
Wave steepness	The ratio of **wave height** to wavelength also known as **sea steepness**
Wave transformation	Change in wave energy due to the action of physical processes
Weibull distribution	A model probability distribution, commonly used in wave analysis
Wind rose	Diagram showing the long-term distribution of wind speed and direction
Wind sea	Wave conditions directly attributable to recent winds, as opposed to swell
Wind set-up	Elevation of the water level over an area directly caused by wind stress on the water surface
Wind stress	The way in which wind transfers energy to the sea surface

The Scottish Office

The Scottish Office commissions applied research to support the formulation, development and evaluation of its policies to improve the quality of the Scottish environment and the life of its people. Research also assists the Scottish Office in meeting its statutory responsibilities.

Historic Scotland

Historic Scotland is an Executive Agency within the Scottish Office.
We discharge the Secretary of State for Scotland's functions in relation to the built heritage - that is, ancient monuments, archaeological sites and landscapes; historic buildings, parks and gardens; and designed landscapes.

We:

- promote the conservation of Scotland's historic buildings and monuments:
  - ∞ directly by looking after the buildings in our care, and
  - ∞ indirectly by compiling a schedule of ancient monuments and a list of historic buildings (both statutory), by providing advice and financial assistance to help conserve them, and, where they cannot be preserved and their recording is no one else's responsibility, by arranging for their survey or excavation;
- promote enjoyment of Scotland's built heritage, in particular by encouraging people to visit the properties in our care;
- advise and educate people on the rich heritage of Scotland's rural, urban and industrial landscape and its many ancient monuments and buildings.

Our aim is to protect Scotland's built heritage for the benefit of present and future generations, and to enhance its understanding and enjoyment.

Scottish Natural Heritage

Scottish Natural Heritage is an independent body established by Parliament in 1992, responsible to the Secretary of State for Scotland. Our task is to secure the conservation and enhancement of Scotland's unique and precious natural heritage - the wildlife, the habitats, the landscapes and the seascapes which has evolved through the long partnership between people and nature. We advise on policies and promote projects that aim to improve the natural heritage and support its sustainable use.

Our aim is to help people to enjoy Scotland's natural heritage responsibly, understand it more fully and use it wisely so that it can be sustained for future generations.